An investigation into technological change and organisational developments in glass production between the Byzantine and Early Islamic Periods (7th-12th centuries) focussing on evidence from Israel

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I, Matthew Phelps, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Ancient Palestine was a major producer and exporter of glass during the Roman and Byzantine periods. The Arab Conquest of the mid-7th century had no initial effect on glass production, however around the 9th-10th century a critical technological change occurred with a shift from natron to plant ash flux. Unresolved questions include the chronology and reasons for change, the origins of the technology, and how the organisation of the industry developed.

Around 300 glass samples taken from vessels dating from the 7th-13th centuries were analysed by LA-ICP-MS. Vessels were sourced from 19 excavated consumption sites at 11 localities across Israel. These excavations were performed by the Israel Antiquities Authority, resulting in well-contextualised vessels of mainly diagnostic types.

The results allowed the characterisation of four natron and four plant ash groups. Vessel chronology suggested a decline in Palestinian production during the 8th century. Changes in this century were evidenced by the appearance of low-soda glass recipes produced at Bet Eli'ezer, the import of large quantities of Egyptian glass, and an influx of plant ash glass in the late 8th century. Falling quantities of Levantine glass types suggested that Palestinian glass production discontinued by the 9th century. This was followed by a decline in Egyptian production 50-100 years later.

Investigation of the potential reasons for the shift to plant ash glass production dismissed the idea of political instability causing disruption of natron extraction and also the effects of climatic change. Instead, economic factors were highlighted, these include long-term pressures on natron supply due to competition from other industries, and rising costs due to state control of extraction and the imposition of tariffs during the 9th century. It was demonstrated that rising costs made natron no longer economically viable for glassmaking.

Investigations into the origins of plant ash glass technologies suggested no clear link to Sasanian glassmaking practices, and instead, it was concluded that plant ash technology in the Eastern Mediterranean was adopted from practices already known to this region. A centralised production model continued after the technological change, with raw glass being exported from Tyre to Palestine and elsewhere. Some vessels were also traded, such as wheel-cut bottles of Mesopotamia origin. A number of smaller compositional types, such as two types of possibly Syrian origin, hinted at the emergence of a non-centralised production model in Syria during the Abbasid period, but this was not conclusive.

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Chapter 1

Introduction and Aims

1.1 Introduction

The Arab conquest of the Byzantine Near East was a critical juncture in world history. It marks the beginning of the end of Antiquity, and the start of developments that led to the Medieval period in this region. The conquest of the mid-7th century brought about rapid and dramatic change in many avenues of life, but conversely, very little change in others. Everyday life was mainly unaffected: land taxes continued to be collected as per Byzantine and Sasanian practices, Christians continued to worship, Greek remained the principal language of the populus and administration in the previously Byzantine territories, towns were not sacked or levelled, and material culture was initially unchanged. However, in other ways, change was abrupt and dramatic. Almost overnight vast territories were removed from Byzantine rule, including Egypt, the richest province. Constantinople lost access to raw materials and agricultural supplies, including the glass producing regions in Egypt and Palestine and the grain producing areas of Egypt. The conquered regions, Egypt, Palestine and Syria, lost access to their Mediterranean trade networks and large overseas markets; however, in many cases these were replaced by new opportunities in the East, in the previously Sasanian territories and beyond (see Figure 1.1). Thus, change was both immediate and gradual depending on the sphere. This project seeks to understand how the glass industry of the Near East, as exemplified by Palestine, reacted and adapted to the dramatic political changes of this transitional period.

Ancient Palestine was situated within modern day Israel and occupied a pre-eminent position in the Mediterranean glass industry for many centuries. It is widely recognised that glass production during the Roman and Byzantine periods conformed to a

centralised production model (Nenna et al 1997; Freestone et al 2000; Degryse 2014). Large tank furnaces have been found in Egypt (e.g. Nenna 2007A; 2010; 2015) and Palestine (Gorin-Rosen 2000; Tal et al. 2004). These furnaces melted many tonnes of sand and natron into large slabs which were broken into chunks and distributed to a large dispersed network of secondary vessel fabrication workshops across the Empire and beyond (Whitehouse 2003). Palestine was therefore at the forefront of glass production and is one of two major regions west of Mesopotamia known to have been producing glass from its raw materials during the Roman and Byzantine periods, along with what appears to have been a localised industry using soda sources in Western Anatolia (Schibille 2011; Rehren at al 2015). How glass production within this region reacted to the Arab conquest and being able to establish the subsequent technological change from natron to plant ash flux, is of major importance to the understanding of regional glass production and supply, but can also inform on some of the wider questions of economic, social and cultural developments taking place as this region transitioned into the Medieval period.

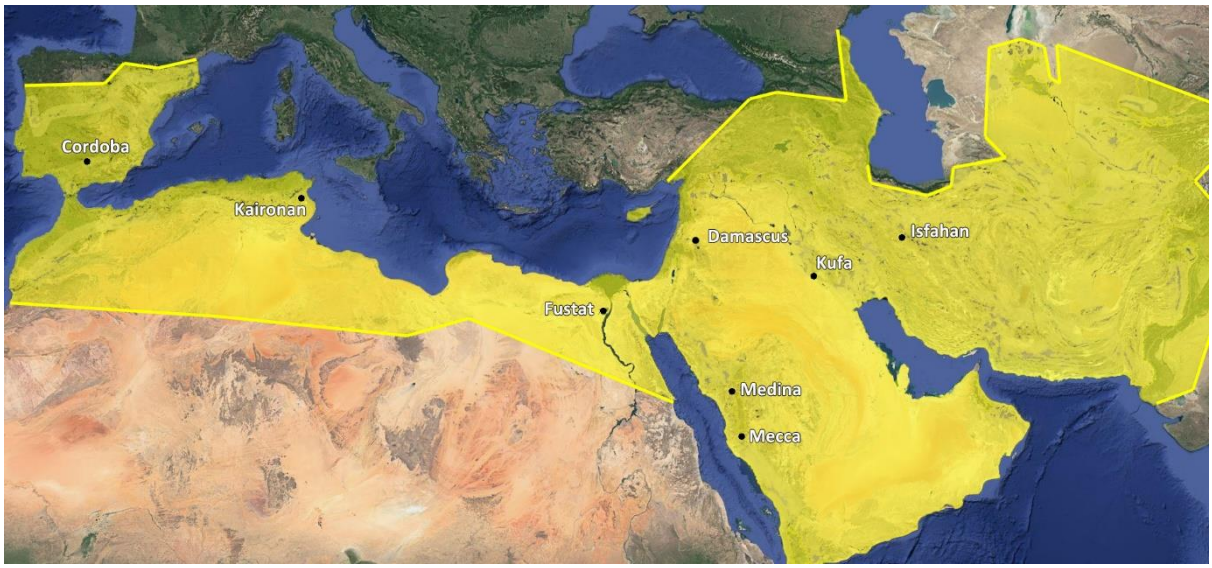


Figure 1.1. The Caliphate's reach at the largest territorial extent during the Umayyad Caliphate in the early 8th century. The Caliphate united regions previously unconnected.

1.1.1 The Research Gap

While Roman and Byzantine glass has been subjected to numerous studies over the last 50 years (see references within Keller 2010) and is now relatively well understood, research within the glass industry of the Islamic period remains less well developed. Although there have been several important compositional studies of Islamic glass (for example analytical work on material from the production sites of Raqqa (Henderson 1999; Henderson et al 2004) and Tyre (Jennings et al 2001; Aldsworth et al 2002; Freestone 2002), and glass from the consumptions sites of Fustat (Kawatoko and Shindo 2010), Nishapur (Kröger 1995) and Raya (Kawatoko 2007; Kato et al 2009; 2010A)), in general, there has been much less emphasis on understanding how the Islamic industry operated as a whole, how it developed post-conquest and how it responded to changing technology. The transition in technology has been discussed in relation to the material at Raqqa (Henderson 2002; Henderson et al 2004; 2005A), but there is limited understanding of what was occurring in other regions, especially of the types of glass in general circulation.

There are several reasons as to why the study of Islamic glass has lagged behind that of Roman and Byzantine material. One concerns the lack of assemblages dating to the requisite periods. This was, in part, due to a general disinterest in Early Islamic material during earlier periods of the 20th century, some of it attributed to political considerations (Petersen 2005A), but also, it has been more recently affected by restrictions on the excavation or access to material in some Near and Middle Eastern countries. Furthermore, in sites where excavations have been conducted, early interpretations were hindered by an inadequate framework for ceramic dating which, up until the early 90s resulted in large discrepancies, particularly affecting Umayyad and early Abbasid contexts (Whitcomb 1990; Magness 1993). There have also been technological limitations. Plant ash glass is compositionally very variable, much more so than natron glass. Glass compositional groups are therefore harder to define, making individual productions sometimes difficult to identify. This can make the investigation of glass supply and trade more problematic, except in cases where distinct production types can be recognised.

These limitations have been mitigated during the last two decades. There is now a clearer understanding of ceramic dating, achieved via the reassessment of earlier sites (Whitcomb 1992), such as the work at Pella by Walmsley (1992) and by Magness (1993) in Jerusalem. New sites have been excavated, providing large amounts of glass from datable consumption sites of Early Islamic context. This is especially true in Israel, where rescue excavations run by the Israel Antiquities Authority have amassed a significant body of glass from numerous excavations with well stratified Islamic period contexts. This includes new excavations of the Islamic period regional capitals of Ramla and Tiberias, and within Jerusalem, resulting in a number of recent publications concerning glass typologies (Gorin-Rosen et al 2010A; Gutreich 2013; Pollak 2007; Hadad 2005) and has allowed investigations into Late Byzantine and Early Islamic primary and secondary production sites (Tal et al 2004; 2008; Freestone et al 2000; 2008A; 2015). Jordan, likewise, has new bodies of analytical results available from the Late Byzantine and Early Islamic period (Abd-Allah 2010; al-Bashaireh et al 2016). Furthermore, new analytical techniques, such as Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS), are aiding provenance studies through the more accurate quantification of minor and trace elements (Shortland et al 2007; Gratuze and Foy 2012; Jackson and Nicholson 2010; Henderson et al 2016). These recent changes have created an ideal opportunity for an in-depth and more holistic investigation of the Early Islamic glass industry.

There are many remaining questions concerning glass production and supply in Palestine and the Near East. The particular focus of this thesis is the technological and organisational change in the glass industry during the later 1st Millennium CE, namely the change in the Eastern Mediterranean from the use of natron to plant ash as a flux and associated developments. This transformation effectively marks the transition from “Roman” to “Islamic” glass production technology, although it does not correspond precisely to the Islamic invasion but post-dates it. Although the change is widely noted and effectively used as a dating horizon in the literature (Freestone and Gorin-Rosen 1999), the chronology of this change and its precursors are imprecise. In the core production area of Palestine information is based predominantly on the analysis of material from primary production sites, which due to the absence of

diagnostic material culture, can often be difficult to date. Furthermore, because the material has been abandoned rather than used to make vessels, it is not clear that it is fully representative of the glass in circulation. The reasons for technological change as currently proposed are determinative, focussing upon the availability of natron as a raw material (Whitehouse 2002; Shortland *et al* 2006), and do not fully consider the relationship of these technologies to developments in social structure, cultural identity, and changes to economic systems. Similarly, the changes to the organisation of the industry have been barely studied, and little is known about the distribution and supply of glass within Israel following the conquest.

1.1.2 Original Contribution

This thesis addresses a number of key outstanding questions relating to the developments in the glass industry during the Early Islamic period through the analysis of well-dated, well-contextualised glass vessels taken from a range of sites across Israel covering the 7th to 12th centuries. The analytical technique to be utilised is LA-ICP-MS, which is able to quantify major, minor and trace elemental data. This enables the identification of technology, group characterisation and provenance investigation, which in turn allows the investigation of how the industry adapted, how production and organisation changed, the process of technological development, and provides insights into the causes and mechanisms of change.

The present project is the first systematic compositional study of Early Islamic vessels covering a large quantity of glass over an extensive time period, from multiple sites, using a modern and accurate analytical technique. Previous work on Islamic glass has tended to be narrowly focused and piecemeal, dealing with single sites, and failing to answer significant, broader reaching, questions. Previous work, for example that on the site of Raqqa (Henderson 1995; 1999; Henderson *et al* 2002; 2004; 2005A), has concentrated on just one production site and concludes little about the regional use of plant ash glass. Brill's (1999) work has provided data from a number of sites, but the data is frequently a mix of vessels and glass working waste, and often lacks reliable dating or context. Other studied assemblages have too few samples to allow robust

conclusions, such as Fischer and McCray's (1999) investigations at Sepphoris. In a recent paper, Henderson et al (2016) have attempted to address wider ranging questions, however, while the study presents new, high quality data, and is able to identify some regional compositional types, it fails to examine enough samples from the same region and from sequential time periods for firm conclusions to be drawn on glass supply, and the paper does not sufficiently interrogate the data to adequately investigate the wider organisational trends. The use of non-destructive X-ray fluorescence in the analyses of several hundred samples from Raya is a much larger study that does provide good chronological progression (Kato *et al* 2009, 2010A), however the analytical technique limits the inter-comparability of the data, although compositional groups have been identified in most cases. The natron-plant ash transition has been better dated in Egypt by the analysis of glass coin weights (Sayre and Smith 1974; Gratuze and Barrandon 1990); nevertheless a lack of reliable data from consumption sites hinders the understanding of how representative these studies were to the wider Egyptian glass industry. For Palestine a number of analyses have been published, but the focus has been on primary and secondary production sites and there is extremely limited data from consumption sites.

1.2 Questions and Aims

The thesis addresses broad but specific questions concerning the developments in glass technology, production and supply in Palestine during the Early Islamic period. It investigates the origins of plant ash glass, and explores the causes and drivers of its adoption. Organisational changes in production and supply will be examined to see how they developed alongside changes in technology and other socio-economic developments of the period. Finally, shifting centres of production and changes in the trade and supply of glass will also be investigated. The questions that will be investigated are:

1. *When did plant ash glass first appear in Palestine?*

Was it as a sudden shift in production or was there a period where both technologies were in use which might indicate a much more gradual development? A gradual transition might suggest that the technology took time to develop and was slow to make inroads into a glass market dominated by natron production, while a faster change might indicate the adoption of a technology wholesale and might also suggest a change or decline in natron production. There is also the question of whether natron glass at any stage returned to production once plant ash glass was introduced. There are very few well-dated studies in Israel, however one notable investigation from Sepphoris suggested that natron glass continued to be prevalent until even late Islamic periods (Fischer and McCray 1999). Similarly, in Raqqa, natron glass is found in 11th century contexts (Henderson et al 2004), although, whether this represents recycled material or the continued primary production is not known. The use of natron glass in later periods is not seen in the well-dated examples from Egypt (Sayre and Smith 1974, Gratuze and Barrandon 1990), which instead suggest a relatively swift and permanent change dating to around the mid-late 9th century.

2. *What were the reasons for the change from natron glass to plant ash glass technology?*

There are many potential factors that may have encouraged the use of plant ash technology, driving its development and adoption. These include potential political and historical events, as well as economic, social and cultural developments of the period. The natron-plant ash transition is frequently mentioned in the literature (Picon *et al* 2008; Saguí 2007; Freestone *et al* 2000; Henderson 1999; Henderson *et al* 2004) but only a few studies tackle this topic directly, for example Whitehouse (2002), Shortland *et al* (2006A) and Henderson (2013, 97-102; 265-6). Most studies tend to suggest that the ultimate factor responsible for the cessation of natron glass production was the development of a natron shortage. Various reasons for this have been proposed. These include political change and instability which led to disruption in natron extraction and trade, as favoured by Whitehouse (2002) and Shortland et al (2006A). Another suggestion is climate change which may have created colder, wetter weather, reducing evaporation and hindering natron formation (Picon and Vichy 2003; Foy and Nenna

2001; Picon *et al* 2008; Saguí 2007, 214). More recently, Henderson (2013) has suggested that in a changing social climate natron glass, was recognised as the product of a 'Byzantine' technology and rejected in favour of a technology identified as 'Islamic', based upon plant ash (Henderson 2013, 266). He suggests that this may be associated with changes in politics or a growth in Islamic identity at the time.

Each of these scenarios implies a different timescale within which the transition would have occurred. Political events or disruptions to trade routes would likely have resulted in a rapid, and also potentially reversible, change. Climatic change or social development, on the other hand, would have occurred on a much more gradual and potentially more permanent basis, which might be seen over a period of a century or more. If related to cultural or social changes, developments in production might reflect changes in dynasty or caliph. These potential explanations are tested against the chronology of sample compositions created in this study.

3. Where did Islamic plant ash technology originate?

It is well known that when the Eastern Mediterranean switched to the use of natron glass in the first millennium BCE, territories to the East of the Euphrates river continued to utilise the traditional raw materials of ancient Mesopotamia glass making (Whitehouse 2005, 67). This continuity was first recognised by Sayre and Smith (1974; Sayre 1967, 152; Smith 1963) in their analysis of Parthian (1st-3rd century) and Sasanian (4-7th century) glass. Our understanding of the Sasanian glass industry is fragmentary, yet enough sites have been investigated for a large scale and extensive glass industry to be recognised (summary in Simpson 2014; see also Whitehouse 2005) which utilised plant ash as a flux (Brill 1999; 2005; Mirti *et al* 2008; 2009). Smith suggested that plant ash glass was *'reintroduced'* from Sasanian territory (Smith 1963, 289) as a direct result of the Islamic conquest bringing East and West together (Sayre and Smith 1974, 65). Whitehouse (2005) also comments on the similarities between Sasanian and later Islamic glass. The extent to which Islamic glass in the Eastern Mediterranean was a continuation of the Sasanian glass industry, or possibly a melding of Byzantine and Sasanian traditions, is unclear. Furthermore, could Islamic plant ash glass of the Levant be a new invention, or even an adoption of an already known plant ash technology

distinct from Sasanian production? These considerations will be examined through the comparison of compositional data, but also through the critical examination of the known production sites in order to investigate if the origins of plant glass production can be traced back to either Sasanian, Roman, or even new technology.

4. *Did the plant ash glass industry continue to use the centralised production model for glass production and supply?*

The Roman and Byzantine natron glass industry was organised into a small number of large scale glass factories, such as those identified in Egypt (Nenna 2007A; 2010; 2015) and Israel (Gorin-Rosen 1995; 2000). This model is suggested to have held until possibly the Early Islamic period as observed from production at Bet Elie'zer (Freestone et al 2000) and the secondary working evidence at Tel Aviv (Freestone et al 2015). It appears that the conquest itself did not alter the organisation of glass production, however, did this change after the shift to plant ash glass production? Did the use of a more widely available flux lead to a proliferation of compositional types which might be associated with a larger number of primary production sites? A model of dispersed production has been proposed for Early Islamic glass manufacture in Syria (Henderson et al 2016), on the other hand, the size and scale of primary production at Tyre suggest that a centralised production model might have continued to operate (Aldsworth et al 2002). This thesis will seek to identify the organisation of Islamic plant ash glass as seen from Palestine by identifying the number of separate compositional groups, studying the provenance of the glass to see how it moved, and through comparison with form, decoration and context, to evaluate if the glass was being traded as vessels or as raw glass. Additionally, it examines the differences in group dominance through time, to explore how different production centres and trade patterns developed.

5. *How did glass production and supply change in Palestine from the 7th to 12th century?*

Finally, the thesis attempts to outline how glass production and supply developed after the conquest until the start of the Crusader period in 1099. It identifies how the

Palestinian glass industry reacted to the appearance of plant ash glass, either through new production sites, or the changing of trade patterns and glass supply. This will contribute to the understanding of how trade networks and the economy of Palestine adapted, not only after the Conquest, but also to the effect of dynastic changes, such as the shift from Umayyad to Abbasid rule and the move of the capital to Baghdad, or developments associated with Fatimid control and the move of the cultural and economic sphere of the region to Fustat.

1.3 Thesis Outline

Chapter 2 provides an historical and economic overview of the period in question, covering both Palestine and the wider Caliphate. It describes the major dynastic shifts and notable caliphs. It also introduces and summarises the historical background and origins of the sites which have provided samples for analysis.

Literature reviews of the current understanding of the Byzantine and Islamic natron glass industry will be presented in Chapter 3 and the Islamic plant ash glass industry in Chapter 4. These chapters critically evaluate current understanding of production and the known compositional groups, and attempt to define regional compositional types for plant ash glass from the available data. Previously analysed assemblages are selected for comparison with the new data, and these choices explained.

Chapter 5 explains the methodology, describing how the data will be generated and utilised. It includes the theoretical framework in which the work is situated, details of sample selection and the sampling criteria employed. It provides information on the sites and assemblages sampled and the contexts of the materials with references to published and unpublished reports. This section describes the analytical and statistical techniques applied and assesses their validity.

The results are found in Chapters 6, 7 and 8. Chapter 6 considers the natron glass, Chapter 7 the plant glass. Chapter 8 combines the compositional findings of both chapters with the contextual information, primarily the dating, in order to investigate changing production trends through time.

The discussion, Chapter 9, synthesises the results to discuss and answer the questions outlined above. Chapter 10 summarises the conclusions and provides suggestions for further work.

The Appendices A-L are presented in the order in which the material is referred to in the text.

1.3.1 Note on non-English words

The author has tended to use simplified forms that commonly appear in English academic use. For example, the Islamic Caliph Abū Jaʿfar al-Manṣūr has been simplified to al-Mansur, as opposed to the more translationally correct al-Manṣūr. I have also opted for the shorter regnal names, rather than full names. For place names, I have selected the name most common to academic literature. For example, the city of Tiberias is from the original Roman name, which is the most well-known and not the current-day Hebrew name *Tveria* or the Arabic *Tabariyyah.*

Chapter 2

The Historical and Archaeological Setting

2.1 Introduction

The second half of the First Millennium CE was a period of great political, economic and cultural change in Palestine and the Near East. Glass production does not occur in a vacuum and developments in the region would have had consequences for the industry. There are many aspects that might impact on glass production, for example, consumer choices might have altered as society and culture developed in the Early Islamic period. Stable political climates can promote economic prosperity, encouraging trade and exchange which in turn can lead to the sharing of ideas and innovations. Instability, on the other hand, can hinder such activities. Therefore, the context in which the glass industry is situated has the potential to profoundly affect how it is organised, the technologies it would use, the type of product that is made, and how it is distributed.

The 7th century saw the Arab conquests of Byzantine and Sasanian territories encompassing the Near and Middle East and North Africa. Arab Muslim rule replaced Christian Byzantine control in Egypt, the Levant and Syria, bringing political, social, cultural and economic changes, forever altered the trajectory of this region, and resulting in a profound and lasting impact on Palestine. This thesis will examine the effects of this on the glass industry and try to understand how and why technological change occurred and the mechanisms and drivers of this change. This section will provide the historical, economic and archaeological background in which the later results will be interpreted (see Chapters 3 and 4 for background to natron and plant ash glass production). It will be presented in three parts; i) an historical overview of Palestine and the wider Caliphate from the 7th century until the Crusader period; ii) description of the diachronic changes in the economy, trade networks and material

culture of Palestine; and iii) an introduction to the archaeology of the sampling sites, their historical context, and an overview of previous glass finds and analyses.

2.2 Early Islamic Palestine and the Caliphate

2.2.1 Historiography

The speed and scale of the Arab conquests was *'astonishing'* (Kennedy 2008, 3). In less than a century an empire had been created stretching from Spain in the West to Transoxania and Afghanistan in the East. The Islamic Caliphate that was to emerge from the conquest ruled as a single entity for over 200 years, only fracturing into smaller autonomous states in the later 9th century. Up until the last few decades of the 20th century the history of post-conquest Palestine was associated with economic decline, population loss, and dramatic cultural and religious transformation (Gil 1992; Von Grunebaum 1970; Safrai 1994, 458; Kaegi 1992, 270-1). Gil, in particular, basing his work on earlier sources, espoused a view portraying violent destruction and decline in post-conquest Palestine (Gil 1992, 61; 160; 169). However, the evidence for this has not borne scrutiny. Many of these early views were based on biased Greek written accounts (Schick 1998, 76) and misdated archaeological data, particularly the Umayyad and Abbasid horizons (see discussion in Magness 2003, 1-2; Whitcomb 1990). Recent excavations using updated chronologies have enabled a re-assessment of the archaeological data for the Early Islamic period (e.g. Whitcomb 1992; Walmsley 1992) demonstrating evidence for continuity in urban settlements. Seminal work by Kennedy (1985) reassessed the evidence for urban decline in Palestine recognising that the deterioration of the Roman 'polis' began before, rather than because of, the conquest. Over a large region, excavations have indicated a patchwork of settlement expansion and contraction post-conquest (Avni 2014; Petersen 2005B; see articles within King and Cameron 1994). Avni (2014) rejects the conquest and its political fall-out as being the main drivers of long-term change in Palestine, suggesting instead the *'intensification and abatement'* model (based on that created by Horden and Purcell 2000 and as used by Whittow (2003) to investigate long-term changes in Late

Antiquity), which suggests that settlements go through periods of population growth, followed by periods of decline, which can be controlled by a myriad of differing factors depending on the circumstances of the location. It is the combination of factors, either acting together or in opposition, which when combined across a region, results in long term change. This model suggests that change is much more complex and needs to be examined in an holistic way to be understood. The archaeology of post conquest Palestine has revealed that change was slow, that the consolidation of the new state took time, and that religious, cultural and settlement change was a much more gradual affair than originally thought (Donner 2008; Levy-Rubin 1998; 2000; Petersen 2005B; Avni 2014; Schick 1995).

2.2.2 Byzantine Palestine

The territories of ancient Palestine are principally within the borders of modern day Israel. Palestine was a Roman province from 70 BCE under the name of Judea, and following the founding of Constantinople in 330 CE became organised into three administrative regions under the Byzantine Empire (Figure 2.1): Palaestina Prima administered at Caesarea Maritima; Palaestina Secunda with a capital at Sepphoris; and Palaestina Tertia controlled from Petra (Safrai 1994; Avni 2014, 27). Phoenice and Arabia, within modern day Lebanon and Jordan respectively, were adjoining regions. Byzantine Palestine of the 5th-6th century is described as economically prosperous, agriculturally productive and politically stable (Morony 2004, 175; Whittow 2010, 72). While long distance trade in Late Antiquity was less intense than during Roman times, Palestine nonetheless continued to have interregional trade routes across the Mediterranean (Kingsley 2009; McCormick 2012), and Palestine and the Empire continued to have sophisticated and monetized economic systems (Whittow 1996, 61).

Figure 2.1. Byzantine period administrative regions around Palestine. Sampling sites are marked in red and labelled. Boundaries based on Avni (2014 Fig 1.2). Ramla is shown but was not founded at this time.

From the 6th century some decline is evident from the archaeological record, with signs of ruralisation of towns, decay of civic infrastructure and declining construction (Kennedy 1985; Morony 2004, 178), for example at Bet Shean (Tsafrir and Foerster 1994; Tsafrir 2009). The reasons for this are disputed but suggestions include recurrent plague and earthquakes (Whittow 1996, 66; Kennedy 2008, 68), fiscal overburdening of the regions by the Byzantine state (see discussion in Whittow 2004, 408-14) and

escalating conflict with the Sasanian Empire (Whittow 2010, 86; Norwich 1998; Browning 1980). The conflict with the Sasanian Empire, which began in 502 CE, is suggested to have had a particularly destabilising effect. It culminated in the conquest of Palestine in 614, with Palestine only being returned to Byzantine rule in around 627. The invasion and subsequent occupation has been reported to have caused much economic and material damage to Palestine (see discussion of Jerusalem in Section 2.4.2), as well as eroding Byzantine control (Kennedy 2008, 70), and may have been an important factor in the rapidity of the Arab conquest.

2.2.3 The Arab Conquest

The invasion of Palestine began in 634 just 2 years after the death of The Prophet Mohammad (for the conquest in depth see Kaegi 1992; Kennedy 2008; Donner 1981; Gil 1992). The decisive battle for Palestine was at Yarmuk (636), where a large Byzantine army suffered conclusive defeat by a much smaller Muslim force (Kennedy 2008, 83-4; Kaegi 1992, 112-146). No significant military resistance is seen after this. In late 636/early 637 Damascus was captured, followed by Jerusalem in 637, and the taking of Caesarea and Ashkelon in 640 (Kaegi 1992, 66-68), Egypt followed in 642 and the Sasanian Empire collapsed in 651. Most cities in Palestine were issued with ultimatums and chose to surrender; this saved much loss of life and material damage. Caesarea was one of the few cities that resisted (Schick 1998, 75-6). The reasons for the speed of the Byzantine collapse have been debated (Kaegi 1992, Gil 1992, Whittow 1996; 2010; Kennedy 2008). Various suggestions include a weakening of Byzantine rule due to the effects of religious schisms, bankruptcy following the Sasanian War and the lengthy Sasanian occupation breaking Byzantine continuity of rule in Palestine. Whittow notes that whatever the reasons the *"willingness of local elites to come to terms with invaders"* (2010, 94) was an important factor in the speed of the conquest.

2.2.4 Byzantine-Islamic Transition and the Formation of the Islamic State

Byzantine and Greek written sources tend to exaggerate the destruction during conquest (Schick 1998, 76). Gil (1992, 61) writes that "*there is no doubt that many of*

the small towns and villages were destroyed during the conquest, and one can imagine that the war and slaughter of the population considerably decreased its numbers" but there is no evidence for this assertion. The conquest is almost invisible archaeologically, with no destruction layers in most cities (Whitcomb 1998, 488; Magness 2003, 177-194; Walmsley 2007, 47 and references within), no change in settlement patterns (Robinson 2010, 198) and no evidence for fiscal or administrative breakdown (Humphreys 2010, 512). The evidence suggests that the Arab conquest had little significant effect on the everyday lives of the population (Milwright 2010A, 44; 2010B, 666).

Figure 2.2. Post-conquest administrative regions in Palestine. Sampling sites marked in red. Boundaries based on Avni (2014, Fig. 1.3).

The regions of Palestine were rearranged into military districts after the conquest (Luz 1997, 27; Figure 2.2). Palaestina Prima and the regions of Negev Desert within Palestine Tertia were incorporated into Jund Filistin, and the capital moved from Caesarea Maritima to Lod (Ludd) at first (although possibly shared with Jerusalem, see Luz 1997, 30), and then Ramla upon its establishment in 715 CE (Avni 2014, 27). Palaestina Secunda was superseded by Jund al-Urdunn, which also included areas of coast originally within the province of Phoenice. The capital of this new region was Tiberias, transferred from Bet Shean. Muslims did not settle amongst the local populations but instead established themselves in newly formed garrison towns such as Fustat in Egypt, Basra and Kufa in Iraq, and later Ramla, or in extramural areas of existing cities, such as at Aleppo (Kennedy 2008, 373). In consequence they did not become assimilated into the local populations, allowing them to hold onto their Muslim Arab identity despite being a minority (Bennison 2011, 5).

Early Islamic rule was by the four *'Rightly Guided'* Caliphs starting with Abu Bakr in 632 who followed The Prophet Mohammad's death. He was succeeded by 'Umar in 634, then 'Uthman from 644 and Ali in 656 (Robinson 2010, 203). The earliest Islamic state formed under 'Umar (ibid, 208) who created the *diwan* system which recorded the distribution of the *'ata*, the stipend paid to Muslim settlers and soldiers (Kennedy 1986, 68). He also introduced the Muslim calendar and the office of the judge (Robinson 2010, 203). 'Umar's use of Byzantine and Sasanian bureaucracies and low taxation set the trend for later Islamic rule. The first civil war (*fitna*) occurred during the short-lived and turbulent reigns of 'Uthman and Ali.

2.2.5 The Umayyad Dynasty: 662-750 CE

Mu'awiya (r. 661-80) was the first caliph of the Umayyad Dynasty. During his long and stable reign strides were taken towards much greater centralisation of the emerging state (Robinson 2010, 204), with the capital moving to Damascus increasing the proximity to the new territories (Humphreys 2010, 516). In Egypt the original Byzantine administration system was expanded and it is during this period that the first documentation of the emerging Islamic State is found (Donner 1986), although

local administration was still controlled by non-Muslims. The death of Mu'awiya was followed by the second civil war and a number of caliphs ruled in quick succession: Yazid in 680; Mu'awiya II in 683; and Marwan ibn al-Hakam in 684. Al-Hakam died in 685 and was succeeded by Abd al-Malik.

Al-Malik's reign (r. 685-705) heralded a period of much greater state development, reform and centralisation. This resulted in a more complex and differentiated state, and it was at this time that a number of important institutions were created (Robinson 2010, Hawting 1986, 61-68; Donner 1986, 293). Developments included reform of the army, increased centralised control of fiscal and administration systems, and the introduction of Arabic as the official language of the administration opening up bureaucratic careers to Arabs (Robinson 2010, 218-9). The process of Arabisation of administration was slow and not completed until 706 in Egypt and 742 in Iran (Cobb 2010, 242), but it was an important stride forward in asserting the dominance of Islamic culture. Al-Malik also reformed coinage and was the first caliph to mint distinct Islamic coins starting from 692 CE (Schick 1998, 95-6; Walmsley 2007, 59-64), replacing coins of Byzantine iconography that were still in production and circulation up to this point. In 696-7 gold coinage with non-figural images and with Arabic only legends were introduced. The new coinage, in conjunction with a new system of weights and measurements also brought in at this time, helped to legitimise and assert government authority (Donner 1986, 289-91). These developments coincided with state patronisation of building projects in Palestine and Syria, including the completion of the Dome of the Rock in Jerusalem in 692, one of the very first examples of Islamic architecture (Johns 2003, 416). Other public works included milestones and road levelling works (Donner 1986, 291). All these changes lead to the developments of Islamic identity and culture at this time, which became expressed in new architecture and the first changes to material culture (Milwright 2010B; Schick 1998, 94; Walmsley 1992, 256; see discussion below). Some Byzantine influences continued however, as evidenced by the ongoing use of mosaics in Umayyad mosques and palaces (see references in Henderson 2013, 255). Other acts during al-Malik's reign further emphasised the dominance of Muslim culture; pigs were banned, as were images of crosses (including the removal of the cross from coinage). Non-muslims were the only

people to pay tax, accentuating the differences between the religious groups, and this, along with the other anti-Christian edicts, meant the number of conversions increased at this time (Humphreys 2010, 521).

Al-Malik was succeeded by his son, Al-Walid (r. 705-715), who continued the reforms. Al-Walid's reign is considered one of the high points of the Umayyad dynasty (Cobb 2010, 227), and it was the period in which the Umayyad caliphate reached its largest territorial extent. Some of the many enactments during this period were to perform land surveys and censuses, mosque construction, irrigation improvements and the expansion of settled regions. Encouragement of conversions also continued (Cobb 2010, 243). Al-Walid's death in 715 was followed by a number of shorter reigns. Sulayman (r. 715-17) founded the city of Ramla, developed new canal systems and began new construction at Mosel (Cobb 2010, 248), as well as building the Great Mosque in Damascus (Humphreys 2010, 521). He was followed by less eventful reigns of Umar II (r. 717-20) and Yazid II (r. 720-4). Hisham (r.724-43), during his longer reign, on the other hand, accomplished much, through the extending diplomatic contacts and strengthening control of taxation in the newly conquered regions (Cobb 2010, 229). He was also a prolific builder, ordering the construction of new mosques and commercial areas (shops, markets, souks) at numerous sites, such as those at Bet Shean (Tsafrir 2009, 80). He also organised the raiding of Byzantine territories, which continued until his defeat in battle in 740. However, nineteen years of warfare and extravagant construction programmes led to poor state finances by the end of his reign (Humphreys 2010, 523-5).

In the later years of Umayyad rule an increasingly large Muslim local population started to erode the privileged position of the elite Arab Muslims. The *'ata* system of tax redistribution and the *diwan* stipend that paid for the upkeep of the tribal armies was overburdened and so the tribal armies were disbanded and supplanted by professional soldiers (Cob 2010, 251). This resulted in factional infighting between competing tribal families within Syria (Cobb 2010, 251-253), and under al-Walid II (743-4) the 3rd civil war broke out. The caliphate, which relied on Syrian troops, was no longer capable of properly administering its territories and the tribal factionalism became further exacerbated by religious divisions between the Kharijite and Shi'a sects

who felt disquiet over the Umayyad interpretation of God. Al-Walid II (r. 743-4) was killed and replaced with Yazid III, followed by revolt and defeat by Marwan II (r. 744-50). The Kharijite revolts continued to grow in the East (Cobb 2010, 259) and culminated in the Abbasid revolution that had started in Kufa, Iraq. It was around this juncture, in 749, that Syria and Palestine were rocked by a serious earthquake, with many cities sustaining extensive damage. Finally, in 750, on the banks of the Tigris, Marwan II's army was defeated by the Abbasid forces, ending the Umayyad dynasty, although sporadic fighting was to continue until 754 (Cobb 2010, 266).

2.2.6 The Rise and Decline of Abbasid Rule in the 8th - 9th Century

The Abbasids were a Shi'a movement, who believed rule should come from the family of the Prophet (Kennedy 1986, 124). They gained a powerbase in Khurasan, establishing enough power to overthrow the Umayyad Dynasty. Abbasid rule would have a profound effect on the Caliphate, moving the core of the empire eastwards. It was during this period that Caliphal power reached its height and when Islamic civilisation made its greatest cultural progress. Kennedy comments that the Abbasid regime was to become *'by far the greatest political power in the Islamic world*' (2006, ix). It was not to last however and by the mid-9th century this power was waning and the grip on the outlying provinces weakened, as dwindling revenues and ineffectual governance led to the appearance of autonomous dynastic states, which eventually led to the breakup of the Caliphate.

Caliph Saffah (r. 750-754) was installed in Damascus as the first Abbasid Caliph but it was under al-Mansur (r. 754-775) that stability became re-established in 762 CE (el-Hibri 2010, 269). This was in the year that al-Mansur relocated the capital to Baghdad, a new city founded on the Tigris River, which shifted power away from the Arab elites in Syria and closer to the Abbasid powerbase in the East. Iraq was a rich agricultural region at this time, the wealthiest province of the caliphate (Hawting 1986, 38) and estimated to have four times the revenue of Egypt (Kennedy 2006, 132). The wealth of the region, along with excellent communication and trade links with other provinces and regions, made the location of Baghdad ideal for a capital. Iraq benefited from this

in increased patronage, in addition to trade. The move also instigated cultural changes, with subsequent caliphs having distinct Sasanian/Persian influences (El-Hibri 2010, 273; 280). The siting of Baghdad along a number of important trade routes led to its transformation into a major commercial centre (Bennison 2011, 71; Kennedy 1986, 147).

Al-Mansur died in 775 and was followed by the less consequential reigns of al-Mahdi and al-Hadi, but then in 786 Caliph Harun al-Rashid came to power. His 23-year reign culminated in a high point in the caliphate and has been described as the *'golden age'* of Islamic rule (Kennedy 2006, 51), a time when economic prosperity reached its zenith (Bennison 2011, 30; Kennedy 1986, 146-7), centred around Baghdad. Significant amounts of long distance trade with India, China and the Baltic regions helped promote a strong craft industry, encouraging wealth generation and raising the wealth of the state to *'unprecedented levels'* (Hodges and Whitehouse 1983, 157). Coins and archaeological finds in Russia, India, China and the Baltic have demonstrated the economic reach of the caliphate at this time (Shatzmiller 2011; el-Hibri 2010, 284). The formation of extra-mural craft zones, like those identified at Raqqa (Henderson et al 2004), helped to spur innovation, such as that in pottery and glazes (Milwright 2010A, 47; Henderson et al 2005; al-Saad 2002;). Progress was also made in the sciences, the arts, as well as the birth of the translation movement in which Greek manuscripts were collected and transcribed (al-Khalili 2012). This was also a period of increased diplomatic engagement, with the Caliph being in contact with Charlemagne of the Holy Roman Empire and with China (Kennedy 1986, 147).

The relocation of the capital to the East was not a disaster for Palestine. Original assessments of economic decline and population loss have not been supported by new well-dated archaeological data (Whitcomb 1992; Walmsley 1992). Even though Gil notes numerous incidents of rebellion during the early Abbasid period and the marginalisation of Arab elites (Gil 1992 279-288), Syro-Palestine appears to remain wealthy and productive into the 9th century (Humphreys 2010, 529). Cities such as Ramla continued to thrive (Avni 2014, 181; Tal and Taxel 2008, 81). Orchestration of renewed war against the Byzantine Empire meant that Harun al-Rashid spent several

years in Raqqa (796-808), his closer proximity brought money and patronage back to Syro-Palestine for a time.

Harun al-Rashid died in 809, and was followed by the *'Great Abbasid Civil War'* (Kennedy 1986, 148) between the brothers al-Amin (r. 809-813) and al-Ma'mun (r. 813-833), which led to a period of protracted instability enduring from 809 to approximately 827. This would permanently damage the Abbasid state, weakening control of the provinces, creating a power vacuum in which semi-autonomous hereditary dynasties formed, like those of the Tahirid Dynasty in Transoxania and Aghlabid rule in North Africa. Furthermore, there grew a reliance on Turkish slave soldiers (*ghilman*) who were used to balance the power of competing Iranian and Arab factions (El-Hibri 2010, 290). Turkish commanders became increasingly influential at the expense of Iranian elites, leading to increasing instability.

Al-Ma'mun died and was replaced by his brother, al-Mu'tasim (r. 833-842). A degree of stability was restored, but continued reliance on Turkish soldiers caused conflict with local troops in Baghdad (El-Hibri 2010, 296) and, as a solution, in 836 a decision was made to relocate the capital to a new location, 60 miles north of Baghdad (Bennison 2011, 38). The newly founded city was Samarra, situated on the eastern bank of the Tigris River, built with large palaces, the Court and residential buildings. Provision was also made for soldiers. However, the location of Samarra was never as favourable as that of Baghdad, either in water provision or communication links (Kennedy 2006, 163). Moreover, the heavy presence of Turkish soldiers, and the separation of the Caliph from Baghdad, meant that the Caliph became increasingly isolated. Al-Mu'tasim was succeeded by al-Mutawakkil (r. 847-861), whose long reign, although stable, was increasingly controlled by Turkish commanders, eventually leading to his assassination in 861 CE. Subsequent caliphs were similarly manipulated, controlled and occasionally assassinated (see Bonner 2010), and while there were some effective caliphs, for example al-Mu'tamid (r. 870-892), who managed to return the Court to Baghdad in 892 CE, weak rule and financial mismanagement during the later 9th century led to irreparable damage to Abbasid control (Bennison 2011, 42)

The effect of the Abbasid civil war in Palestine was one of instability and of declining political control starting in the 9th century and continuing into the 10th. Political

vacuum precipitated revolts, social disturbances and tribal rebellion (Schick 1998, 77; Gil 1992, 294-306; Humphreys 2010), which worsened following the assassination of al-Mutawakkil in 861. Out of the turmoil of the period emerged Ahmad ibn Tulun, a Turkish guard sent to Egypt as governor who ultimately assumed control of the province and founded the Tulunid Dynasty in Egypt (r. 868-906; Bianquis 1998). While nominally loyal to the Abbasid caliphate, the Tulinids ruled autonomously, withholding revenues to Baghdad, and creating a separate army. In 878 (Schick 1998; Gil 1992, 307) Tulun took control of Palestine by force, and subsequently wrested control of Syria as far as the Byzantine border. In 906 changing fortunes meant that the Governorship of Egypt and rule of Palestine returned to Abbasid jurisdiction, however, this was short lived and continued ineffective rule led to the founding of the Ikhshidid Dynasty (r. 935-969) in Egypt and Syro-Palestine (Gil 1992, 326). Thirty years later the arrival of the Fatimids from North Africa heralded a period of new prosperity in Palestine.

2.2.7 Fatimid rule in Palestine – 10th-11th century

The Abbasid Caliphate of the late 10th and 11th centuries was much diminished in power. Falling revenues in Iraq due to mismanagement of the irrigation systems had caused a financial crisis (Kennedy 2010, 360). Agricultural land became *'ruined and impoverished'* (ibid), leading to permanent loss of fertility in some areas. The caliphate no longer had money to enforce rule and power was ceded to autonomous dynasties, while the role of the caliph was reduced to a religious figurehead (Kennedy 2010 362; Bennison 2011, 39).

As Abbasid rule in Iraq diminished, so Egypt expanded in power. Under self-rule Egypt was able to withhold revenues, enabling it to fund its own infrastructure and expand its economy (Bianquis 1998, 98). Strengthening trade ties between Egypt and Palestine during the periods of shared rule helped spread this wealth to Syro-Palestine. However, at this time in North Africa, a new religious sect was taking root. Although originating in Iraq, the Isma'iles sect had fled to North Africa, and after advancing its powerbase, was able to overthrow the semi-autonomous Aghlabids Dynasty in 909, creating the Fatimid Caliphate in the process (Bennison 2011 40). In 969, after a

number of aborted attempts, they succeeded in taking Egypt, subsequently followed by Palestine and Syria (Eddé 2010). Intermittent civil war ensued lasting into the 11th century, what Gil describes as an '*unceasing war that destroyed Palestine'* (Gil 1992, 336), however between 1029 and the Seljuq invasion in 1071 a 40-year period of stability was created. This period of relative calm allowed economic growth in Palestine, generating prosperity, and facilitating significant economic and population expansion (Schick 1998 78). This came to a dramatic end with Seljuq rule in 1071; heavy taxes led to rebellions in 1078 (Gil 1992, 415-20) and Seljuq rule was beset with unrest. The later 11th century also saw periodic severe drought (Gil 1992, 400-1; Ellenblum 2012) and two large earthquakes in 1033 and 1068 with such circumstances leading to substantial destruction within Palestine. In 1098 the Fatimids re-took Palestine, only for the Crusader armies to invade Palestine, occupying Jerusalem in 1099 (Eddé 2010, 177). Areas of Palestine were only restored to Muslim rule in 1190 (Bennison 2011, 51).

2.3 Trade, Economy and Material Culture

2.3.1 Trade and Economy

The Palestinian economy of the 5th-6th century was centred on Mediterranean trade networks. There was scant trade with the Sasanian Empire, in part due to conflicts (Kingsley 2009, 33-34), and any trade directed towards India, strong in Roman periods, had diminished by this time. While the Byzantine economy was strong in the 5-6th century, by the mid-6th century there were signs of contraction, with exchange in Palestine becoming increasingly local. This led to the closure of some Mediterranean ports in the late 6th/7th century (Morony 2004, 178-9). The Arab conquest caused political boundaries to be redrawn, and the conflict forestalled Mediterranean trade with Constantinople, the Balkans and Southern Europe. Kingsley, in a study of eastern Mediterranean shipwrecks, identified no shipwrecks in the period after 650 CE (2009, 35), although work by Haldon (2012, 105) does indicate limited movement of ceramics

between Egypt, the Levant and the Byzantine Empire during the 8th and 9th century. The conquest did, however, unite Palestine with prosperous Sasanian territories, the Silk Road, and via the Persian Gulf ports, India (Bennison 2011, 137). Trade in Palestine therefore turned inland and eastwards post-conquest. The expansion of Islamic territory into North Africa during the Umayyad period, and to Spain in the West, as well as Kurasan, Transoxania and Afghanistan in the East, connected remote and distant lands under one state, one religion and one language, permitting trade to flourish. So while markets in the Mediterranean became no longer viable, they were supplanted by new, potentially more profitable routes.

The transformation of trade had a beneficial impact on the Syro-Palestine economy. Although port cities such as Caesarea suffered due to the decline in maritime routes (see later), inland cities along major road networks such as Tiberias and Ramla thrived (Luz 1997, 43; Khamis 2013, 14). Expansion and growth was particularly pronounced under Caliphs Al-Malik, al-Walid, and Hisham, with the economy during these reigns driven by imperial expansion, administrative centralisation in Syria and greater regional interdependence (Cobb 2010, 244; 249). This was further aided by infrastructural investment with the building of new markets and shops in cities such as Bet Shean, Tiberias and Jarash during the late 7th/early 8th century (Walmsley 2007; Tsafrir and Foerster 1994; Cobb 2010, 248). There are also documented records of regional networks of trade fairs linking Jordan and Damascus, and a separate network joining the cities and towns of Palestine (Binggeli 2012). Fairs tended to be positioned at crossroads of major routes, demonstrating how goods were circulated. Walmsley, (2012) in his work on ceramic distributions in Palestine and Jordan, demonstrated localised distribution around pottery production sites during the Umayyad period of often 30-50km in size. Trading range could increase by up to 100km for some higher quality wares provided that a second trade was made from a market at the edge of the catchment area (ibid, 317). He noted the *'highly regional nature of ceramic production and distribution'* during the 7th-late 8th century (ibid, 316) and the lack of wares from alternative regions. Growth in the regional economy was particularly assisted by the redistribution of taxes to Muslims. This played a large part in the stimulation of consumerism and development of a strong craft industry (Bennison 2011, 137).

Bennison (ibid) and Essa and Ali (2010, 46) further remark that Islamic and Arabic culture was particularly conducive and encouraging of trade and mercantile activities, while the Hajj (pilgrimage to Mecca) helped boost the movement of people and the flow of goods. This allowed the development of a *'well integrated and financially sophisticated business sector'* (Banaji 2010, 174) during the early Islamic period.

The move of the capital to Baghdad during the Abbasid Caliphate and the stable reign of Harun al-Rashid created a period of great economic prosperity in which the quantities of produce and traded goods reached its pinnacle, and long distance trade became increasingly important (Walmsley 2000). On a more regional scale, trade along the Euphrates between Baghdad, al-Raqqa and Aleppo was opened up, creating an important inland transport network with trade fairs at sites along the way (Binggeli 2012, 296). Extensive long distance trade developed with India, China, Russia and the Baltic regions, as evidenced by glass finds in China (Kinoshita 2009) and Islamic silver coinage hoards in the Baltic (Noonan 1998). In addition, there was an expansion of Indian Ocean trade from the Persian Gulf ports of Basra and Siraf (Milwright 2010B, 679-80; Shatzmiller 2011). The movement of goods and people, as well as the joining of cultural regions into one political entity and the creation of large industrial zones at cities such as Raqqa, Fustat and Nishapur (Milwright 2010A 57; Henderson et al 2004; Heidemann 2006) had a positive effect on technology and innovation in this period as seen through advances in ceramic glazing (Mason and Tite 1997; Milwright 2010A, 47), developments of stonepaste (Mason and Tite 1994) and in new styles in ceramics and glass (see Section 4.1 for discussion of glass). Economic growth was further encouraged by high wages, a monetized economy and low taxes (Shatzmiller 2011, 170, 174).

Despite the changes in political status, the economy of Palestine remained predominately strong during the 9th century. During the later 9th and 10th centuries the reopening of Mediterranean trade routes to Southern Europe and the Byzantine Empire is evidenced from shipwrecks (Kingsley 2009, 35; McCormick 2012) and documentary sources (Jacoby 2009), and this helped to accelerate economic growth in Palestine, although Mediterranean trade was still disrupted by periodic conflicts. The economic collapse in Iraq during the later 9th and 10th centuries led Palestinian trade to

turn towards Egypt, North Africa and the Mediterranean (Schick 1998, 78). This trade was further enhanced in the late 10th and 11th century as goods travelling from the Indian Ocean and Far East increasingly went through Red Sea ports to Egypt and not the Persian Ports (Jacoby 2009, 281). Such goods were then forwarded from Alexandria to Constantinople via the Levantine ports (ibid). Commerce between the Fatimid Caliphate and Byzantine Empire was further aided by the Italian trading states, such as Venice, in the 10th century (Milwright 2010A, 164). The archaeological evidence for trade can be shown in the quantities of Islamic glazed wares at coastal sites in Yemen, East Africa, Sri Lanka and Thailand (see references in Milwright 2010A, 679-81). Similarly, the economic wealth within Palestine is evident from hoards of coins and metals found at Tiberias and Caesarea (Khamis 2013; Rosen-Ayalon 2006, 81).

Our knowledge of trade and business during the 10th and 11th century is greatly enhanced and facilitated by the documents of the Cairo Geniza. These are a collection of legal documents discovered in Egypt, the contents of which relate to commercial transactions mainly during the Fatimid period (Goitein 1967). Although biased towards the activities of Jewish families and centred on Egypt, they provide a valuable insight into trade and business activities. The Geniza indicates that trade in Egypt was dominated by maritime routes between Tunisia and Sicily in the Fatimid period, with these locations forming the hubs of Mediterranean trade. Movement of goods between Egypt and Palestine is also documented, with fourteen Levantine ports listed, of which the most important were Ashkelon, Acre, Tyre, Tripoli and al-Lādhiqiyya (Goitein 1967, 212). The volume of letters indicated brisk trade between these ports and the principal ports of Egypt: Alexandria, Rosetta, Damietta and Tinnis (Goitein 1967, 213). The Geniza signals a much less regular trade with Constantinople, although, foreign trade, such as that to southern France and Italy, was generally outside the purview of Jewish merchants and often controlled by foreigners (ibid, 214). There were also overland routes between North Africa and Fustat, and Fustat to Damascus (ibid, 276), these were more expensive but able to fill seasonal gaps as boats did not sail during the winter months (ibid, 277). The principal produce of Palestine traded to Egypt was olives, dried figs, raisins, silk, cotton and soap, with cheese coming

from Jerusalem, mirrors, lamp jars and needles from Bet Shean, and indigo and dates from Tiberias (Le Strange 1890, 18-19). This was recorded by al-Muqaddasi (945/6-991), a well-travelled Arab geographer writing in the late 10th century and translated in Le Strange (1890). Al-Muqaddasi further comments that trade between Egypt and Syria was *'considerable'* (ibid, 18).

The Serçe Limanı shipwreck (Bass et al 2009), found off the southern coast of Turkey, is another key indicator of trade, and in particular, that of the trade in glass from the Levant to the Byzantine Empire and Europe. The ship was carrying a selection of trade goods, most likely from Palestine to a final destination suggested at Constantinople. These goods included amphora which might have held wine and olive oil, glazed ceramics, and two tonnes of glass cullet and a further tonne of raw glass chunks. Analysis suggests that much of this glass could have been produced at Tyre (Brill 2009). Dated to around 1024-25 it demonstrates a trade in glass between the Fatimid Caliphate and Byzantine Empire. There is also a document in the Geniza, dated 1011, concerning the movement of 37 bales of glass from Tyre to Fustat, thought to amount to around 9 tonnes (Carboni et al 2003, 148; see Chapter 4). This demonstrates the movement of large quantities of raw glass up and down the Levantine coast to Egypt and the Byzantine territory during the Fatimid period.

During Crusader rule in the 12th century trade in the Levant was further opened up to Europe, however, Milwright (2010A, 165) notes that this was mainly for expensive Islamic and Chinese goods. Local wares do not appear to be traded and Frankish goods made little inroad into Islamic regions (ibid, 165-7).

2.3.2 Developments in Material Culture

There was no initial change in the material culture of Palestine immediately post-conquest (Milwright 2010B, 666; Schick 1998, 94). Walmsley (2007, 49-59) describes approximately three trends in Early Islamic pottery (for more in-depth analysis see Walmsley 1995; Whitcomb 1988; Sauer and Magness 1997; and for wider changes to material culture Milwright 2010B) and these changes are mirrored in the glass (see Chapter 4). At first, Byzantine forms continued to be used in Palestine and it is only in

the late 7th/early 8th century that new ceramic forms start to emerge. These forms, however, were still based upon pre-existing styles present in Palestine and Syria before the conquest (Walmsley 2007, 53) and do not herald a sea-change in material culture of the region. The dating of this change coincides with the reforms of al-Malik (ibid, 56) and al-Walid, which saw the introduction of Islamic coinage and weights, the building of the first Islamic monuments, and in general, a growth in Islamic identity.

A much more dramatic and significant transformation in pottery style occurred during the late 8th/early 9th century, which continued throughout the 9th century. Walmsley described the use of *'new and exotic pottery types'* (2007, 54). These styles, which included new colourful forms and glazed pale cream wares, originated in Iraq, and first appeared during the height of the Abbasid Caliphate, particularly under Harun al-Rashid. While distinctly Islamic, the forms displayed Sasanian/Persian influences. The rapid changes resulted from technological and stylistic innovations during the late 8th/9th century, which was stimulated by the transfer of Caliphal power eastwards. This was additionally assisted by the opening up of trade and increased movement of craft workers. In the 11th century, a final change is noted in the growth in use of hand-made pottery in Palestine (Walmsley 2007, 58).

2.4 Historical Background to the Sampling Sites

The altered political landscape of Palestine after the Arab conquest brought continuity but also transformation. Slow and gradual material culture change during the 7th and early 8th century eventually gave way to more rapid innovation during the late 8th/early 9th century. Throughout the whole of the Early Islamic period gradual change is evident in the culture and society of the region. This thesis investigates glass from excavations at 11 locations in modern day Israel. This final section presents an historical and archaeological overview of the sampling locations in order to represent the sites within their regional context and wider historical narrative. The individual excavations will be reported in detail in Chapter 5. The sites are divided into four groups: two provincial capitals – Ramla and Tiberias; four urban centres – Caesarea,

Jerusalem, Bet Shean and Sepphoris; two coastal military installations – Ashdod Yam and Ha-Bonim; and three rural villages – Ahihud, Nahal Shoval and Tel Rosh. The sites are marked in Figure 2.2.

2.4.1 The Provincial Capitals - Ramla and Tiberias

Ramla and Tiberias were regional capitals of Jund Filastin and al-Urdunn respectively. Both became rich administrative and commercial centres; however, the origins of these cities were distinctly different.

Ramla was founded in c.715 by Sulayman prior to becoming Caliph (r. 715-717). It replaced Lod as the capital of Jund Filastin (Schick 1998, 84) and eventually became the largest city in Palestine at around 150-250 hectares (ha; Luz 1997, 40-1; Whitcomb 1995). Ramla was unique in Palestine as the only city established post-conquest and the only city to be built on Muslim principles (Luz 1997, 27). It was situated on a densely populated plain in a rich agricultural region on a crossroads between the routes running from Damascus to Egypt and Jerusalem to the Coast (Avni 2014, 160).

Ramla has had approximately 200 rescue excavations since 1990, which have been able to create a much clearer image of the city's development during the early Islamic period. The first 70 years saw the construction of monumental buildings and development of residential districts (Avni 2014 181-183). It was designed in a classical grid pattern around the White Mosque at the centre, with administrative buildings and a palace. Markets lined the main streets leading to the 8 city gates. Major expansion occurred during the 9th and 10th centuries, as evident from residential districts outside the city wall (ibid, 181). Excavations of extramural industrial areas to the south dating to the Umayyad 8th to Abbasid 10th centuries provide some context to the economic growth of Ramla (Tal and Taxel 2008, 81). This area was most likely used for flax and linen production (ibid, 123), one of the major industries of Ramla, though this was to contract in the late 10th/early 11th century due to Egypt being granted monopoly rights to production (ibid, 123). The reasons for the prosperity of Ramla were down to its centrally placed location, its rich hinterland, and its role as an administrative centre. It was to become an '*international trading emporium*' (Luz 1997; 43) and archaeological evidence suggests that Ramla was unaffected by the rife political instability during the

Abbasid and later periods (Avni 2014, 181). This was despite the city being taken forcibly by the Tulinid, Ikhshidid and Fatimid regimes. The city reached its height of size and population in the 10th and early 11th century, becoming the largest city in Palestine. However, the second half of the 11th century saw Ramla's collapse (Avni 2014, 183) as a result of severe political instability due to Fatimid infighting, tribal incursions, and the Seljuq invasion. These setbacks were compounded by earthquakes in 1033 and 1068, which were devastating for the city (Petersen 2005B; Anvi 2014, 183). Some areas were not resettled until modern times. During the Crusader period much of the remaining population moved to Ashkelon.

Tiberias (*Tveria; Tabariyyah*) was a Roman city founded in 20 CE by Herod Antipas located on the western shore of the Sea of Galilee. It became an important Jewish centre holding the Jewish Patriarch from the 3rd century (Stacey et al 2004, 1) and reaching its largest spatial extent under Justinian (r. 527-565), who built the substantial city walls (Hirschfeld 2004, 220). Tiberias has been subject to a number of large excavations over the last century, summarised in Stacey *et al* (2004 9-10). Notable excavations in the old city by Hirschfeld (2004) and Hirschfeld and Gutfeld (2008) found extensive monuments including a theatre, baths, colonnaded streets and markets.

Tiberias surrendered during the Arab Conquest in 635 CE and avoided serious damage. It was declared the capital of the newly created military district of Jund al'Urdunn, and was to benefit from this role and from its proximity to Damascus along the main Egypt to Damascus road (Khamis 2013 14). Tiberias became wealthy, as noted from rich material culture, (Hirschfeld 2004, 128) and grew beyond its Byzantine city limits (Avni 2014, 75). A major earthquake in 749 caused extensive damage, but the city was rebuilt and not permanently affected. The Abbasid period was one of instability lasting from the 9th to 11th centuries with frequent raiding interspersed with periods of peace. However, strengthened ties with Egypt during the late 9th and 10th century proved beneficial, and as the Fatimid regime consolidated power in the later 10th and 11th century Tiberias grew more prosperous as it became more closely linked to the larger Mediterranean trade network (Stacey et al 2004, 3). The Egyptian famines of the late 10th and early 11th century were also seen to benefit Tiberias as it was an exporter of

agricultural produce such as wine, olive oil and dried fruits. These goods were traded from the ports of Acre (Akko), Tyre and Haifa. Stacey notes that a *'flourishing sea-borne trade'* grew between Palestine and Egypt, Byzantine and European markets (Stacey et al 2004, 6). In 1033 and 1068 major earthquakes devastated Tiberias (Khamis 2013 14) and with increasing political instability, signs of decline are seen in the hoarding of precious metals and abandoning of buildings (Khamis 2013; Avni 2014, 89). The city was taken by the Seljuqs in 1071. By the 1080s the city was practically abandoned (Avni 2014, 87), and any remaining population fled in the wake of the Crusaders in 1099. The Crusaders proceeded to build a new city to the north of the old city wall covering just a fifth of the city's former size.

Excavations have revealed large quantities of glass from both Ramla and Tiberias. From South Ramla 400 fragments from the Umayyad to Fatimid periods are published (Jackson-Tal 2008). Another 43 samples are published from a total of 470 fragments uncovered from salvage excavations in Ramla (Gorin-Rosen and Katsnelson 2005). Excavations near the White Mosque produced an important assemblage, of which 133 of the 750 diagnostic fragments, many from sealed and datable contexts, are described by Gorin-Rosen (2010A). She notes the rich variety of vessel types, especially during the Fatimid period where particularly high quality glass with cut decoration are found; some of which have parallels with Nishapur and Fustat (ibid, 250). Pollak (2007, 131) in an investigation of some of the thousands of glass fragments uncovered from Marcus Street, also emphasised the quality and variety of vessel types, noting that some high quality vessels were probably imported.

Large and significant assemblages of glass have come from Tiberias (Lester 2004A; 2004B; Hadad 2008; Amitai-Preiss 2004). The 1973-74 excavations (Lester 2004A) collected over 10 thousand fragments from residential and commercial contexts covering five stratified layers. Of the thousands of vessels 1927 were selected for study and 200 described (ibid). The vessels demonstrate development through time, with Late Byzantine/Umayyad and Early Abbasid periods characterised by bluish-green glass (ibid, 168). There is then a *'transitional period'* (ibid, 216) containing new fabrics and vessels types. And lastly, the Fatimid period contexts contained glass made with '*thicker, more brittle'* fabrics with numerous bubbles (ibid, 168). Many forms of this

period show close similarities to the Serçe Limanı types, most of which were undecorated free blown vessels. Of the decorated types, the majority was of cut glass. Hadad (2008) reported glass excavated from the House of the Bronzes, publishing 135 objects dating predominately to the Abbasid-Fatimid period, and also noting the high proportion of wheel cut examples (ibid, 167). Regional differences were identified in comparisons to Bet Shean, for example mould-blown bowls and bottles are rare in Tiberias but very common in Bet Shean, alternatively incised vessels at Bet Shean are common but very rare at Tiberias (ibid, 175-6). This demonstrates a level of regional variation.

2.4.2 Urban Centres – Bet Shean, Caesarea, Sepphoris and Jerusalem

Glass was additionally collected from excavations at four established urban centres. Two of these were inland commercial cities, one was a port city, and the other was a religious centre. Not all of these cities benefited from the conquest. Caesarea lost its link to Mediterranean trade routes, as well as its capital status along with Bet Shean, and Sepphoris was damaged during the invasion. Jerusalem, on the other hand, continued to prosper. However, by the end of the 11th century all of these cities manifested signs of sharp decline.

Bet Shean (*Scythopolis, Baysān*) was capital of Palestine Secunda from the 4th century and covered an estimated 160 ha (estimated 30-40 thousand people) at its peak in the mid-6th century, the third largest city after Jerusalem and Caesarea (Tsafrir 2009, 64; Tsafrir and Foerster 1994). It contained impressive monumental buildings, colonnaded streets, a theatre, a bath house, a temple and a hippodrome (Avni 2014, 56). The city is located in a fertile, densely settled region, on the crossroads of the routes connecting Egypt and the Coast to Syria and Mesopotamia, and the Jordan Valley Road which connects Syria to Jerusalem and central Palestine, enabling Bet Shean to become an important commercial centre. Descriptions of excavations in the city can be found in Mazor and Bar-Nathan (1998) and Mazor and Najjar (2007).

The city surrendered to the Muslims in 635 CE and no destruction layers have been identified for this or the Persian invasion (Tsafrir and Foerster 1994). Studies have

concluded that the city began to decline during the 6th century, which continued into the Early Islamic period (Kennedy 1985) as seen from the deterioration of civic infrastructure, blocked drainage channels and infilling of streets (Tsafrir and Foerster 1994). The loss of its administrative role inevitably aided its decline, which was subsequently compounded by earthquakes in 659/660 causing some areas of the centre to be abandoned. New commercial buildings and a market complex was constructed under Caliph Hisham (r. 724-743), but another major earthquake in 749 led to further destruction (Avni 2014, 65) and caused the old city centre to be abandoned completely (Arubas 2005, 2). Avni (ibid, 65) disputes that the city failed to recover from the earthquake, as suggested by other authors (e.g. Tsafrir and Foerster 1994), citing construction of new mosques and residential buildings. The city continued to *'flourish'* according to Avni (ibid, 68) until the 10-11th century but on a much smaller scale than in previous periods, now being described as a *'relatively small town'* (Tsafrir and Foerster 1994, 113). The Crusader period saw continued occupation in the 12th century of two of the three areas of the remaining city, and a Crusader Fortress was built. These areas were re-occupied after recapture by the Ayyubids and were inhabited into the Mamluk period (Arubas 2005, 2).

Caesarea Maritima was established by Herod the Great in 22 BCE. Its extensive deep harbour facilitated Caesarea becoming an important and thriving port city. The city was at its greatest extent in the 4th century with an estimated population of 35-100 thousand, with walls encompassing approximately 110 ha, making it the largest city in Palestine at that time (Patrich 2011, 94). Caesarea functioned as a trade hub and an administrative and political centre. It also contained several monumental buildings, including large churches, palaces, a theatre and a hippodrome. During the 5-6th centuries the city began to decline, in part due to loss of some administrative power to Bet Shean, capital of Palaestina Secunda (Patrich 2011, 91). Caesarea has been subject to a series of extensive excavations, and whilst the Islamic and Crusader periods have often been neglected in favour of the Roman and Byzantine material, a number of major excavations tackling the Islamic period have been published (see Arnon 2008; Patrich 2008). For a history of excavations at Caesarea see Raban and Holum (1996).

Caesarea had close ties to the Byzantine Empire and was besieged for 7 years during the invasion. Its coastal location meant it could be supplied by sea and only fell in 640 CE. During this time much of the elite, as well as Christian and Samaritan populations, fled (Patrich 2011, 114; Avni 2014, 45-7). Although the city held on to some of its administrative role post-conquest, it was subjected to Byzantine raiding, and was occupied by the Byzantines between 680-690 (Petersen 2005B, 86; Patrich 2011, 154). It was only under al-Malik (r. 685-705) that repairs were made, including the building of a garrison and mosque. In the 8th century new city walls were built, however they encompassed just a tenth of the city's former size. The founding of Ramla in c. 715 removed Caesarea's remaining administrative functions, and along with the disappearance of Mediterranean trade and the instability of the coastal region meant the city was not able to recover economically or in population in the way that many inland cities did. The 749 earthquake caused much destruction but the late 9th/early 10th century saw some new building and prosperity increased, reaching its height in the late 10th century (Avni 2014 51). Pottery finds attest to a growth in trade between Palestine, Egypt, Europe and Byzantine (Arnon 2008, 54), however this was short-lived and instability in the mid-11th century led to a steep decline (Avni 2014, 51). In 1101 the city was taken by Crusaders, and after their ousting in 1265, the city was abandoned and never reoccupied.

Sepphoris (*Tzippori, Saffuriyyah*) lies in the richest area of Galilee with fertile land and ample water supplies. It has a long history of occupation with permanent settlement from the Hellenistic period (Nagy et al 1996, 29). It was well connected by the main Jordan Valley road and the coastal road between Egypt and Caesarea, which allowed it to thrive from trade and commerce (Meyers *et al* 1992, 3). Its largest extent was under Byzantine rule with an estimated population of 15-20 thousand and an area of 40 ha (Weiss and Netzer 1996, 81). For a history of excavations over the last 30 years see Strange *et al* (2006).

The city was taken by force during the Arab conquest and may have also suffered during the Sasanian invasion 20 years earlier. Fire damage is recorded, but cannot be accurately dated (Weiss and Netzer 1996, 86). Petersen (2005B, 75) suggests the damage could even relate to the 749 earthquake. Ward (1996, 92) comments that

some of the population may have fled and that others may have been killed during the invasion, thereby causing population reduction. Plagues and earthquakes in the 7th century probably diminished the population still further (ibid, 96). Sepphoris was not settled by the Arabs post conquest, nor did it benefit from any administrative roles, and there is clear evidence for urban decline in the abandonment of civic buildings, synagogues and churches from the 7th/8th century. There was also a shift of the town centre southwards, which could have been due to the 749 earthquake (Avni 2014, 216). The city continued to be inhabited but with a much decreased population (ibid, 217). It was taken by the Crusaders in 1099 and continued to be occupied.

Jerusalem is unique in being a religious centre for the three Abrahamic religions. Situated on a plateau in the Judean Mountains around 700m above sea level it has been permanently settled since around the Early Bronze Age (Franken 2007, 48). Jerusalem was badly damaged during the Roman siege and sacking in 70 CE, and again during later Jewish revolts. In the 2nd century the city was renamed Aelia Capitolina and rebuilt on a Roman grid plan under Emperor Hadrian (Graber 1996, 24). In the 4th century the Christianising of the Empire led to pilgrimages and population growth (Schick 2007, 169). City walls were built in the late 3rd/early 4th century and extended to include Mount Zion and the City of David in the south during the 5th century, and it was during the 6th century that the city reached its zenith with an estimated population of 50-70,000 people (Avni 2014, 109). Jews were banned from Jerusalem during Byzantine rule (ibid, 125). Due the city's importance, particularly regarding Biblical history, it has seen an estimated 1700 excavations over the last 150 years (ibid, 115). For a list of archaeological excavations in Jerusalem see Bieberstein and Bloedhorn (1994), while summaries can be found in Kloner (2003) and Gutfeld (2011), and an evaluation of the archaeology of Early Islamic Jerusalem in Galor and Avni (2011) and Avni (2014).

A number of authors (Schick 2007, 179-80; Graber 1996, 41-2) report the *'devastating'* effects of the Persian invasion and occupation from 614-628. The siege, sacking and forced removal of the population most likely reduced the size of the city at this time. Jerusalem was briefly reoccupied by the Byzantine Empire but surrendered to the Muslims by treaty in 638 (Avni 2014, 113). Post-conquest saw no major changes to the

Christian population and Jews were allowed to return to the city. The period that followed saw slow and gradual change, churches and monasteries continued to be built (Avni 2011A, 6) but a number of large Muslim construction projects commenced during Umayyad rule. These were mainly concentrated in developments around the Temple Mount, transforming the area into a Muslim district, with the Temple Mount itself being renamed the al-Haram al-Sharif. Monumental constructions included the Dome of the Rock, which was completed in 692 under al-Malik, the first Muslim monument to be constructed, and this was followed by the al-Aqsa Mosque completed under al-Walid. These, and several other monumental buildings built to the south and west of the Haram, created a Muslim hub in the eastern part of the walled city, whilst Christians continued to concentrate in the west and north (ibid).

In the 8th century new shops and markets (Avni 2014, 121) were constructed opposite the Haram and along the main arteries of the city. The following 9th and 10th centuries were periods of relative prosperity boosted by strong local trade and incoming pilgrims (ibid, 123). Jerusalem continued to be a Christian dominated society, however this began to alter with the increased persecution of Christians in the 11th century. In 1009 al-Hakim destroyed the church of the Holy Sepulchre (although it was rebuilt soon after) and Muslims started to settle into previously Christian zones. The second half of the 11th century was a period of instability and decline in Jerusalem, as in many other Palestinian cities (ibid, 114). Evidence for this is in the contraction of the city limits around the southern edge of the city to their current day extent, suggesting population decline (ibid, 116). The 1033 earthquake might have also damaged the southern city wall. In 1047 Nasir-I Khursraw estimated the population at 20 thousand, with much of the reduction probably occurring in the 10th and 11th centuries (Avni 2014, 158). The Seljuqs took Jerusalem in 1073, followed by Fatimid recapture in 1098 and Crusader conquest in 1099. During the Crusader capture the city was sacked and both Muslims and Jews were massacred, subsequent migration by Christians repopulated the city after this date.

Glass is a common find at these large urban sites. Bet Shean contained a very well preserved glass workshop incorporating a furnace with intact firing chamber (Mazor and Bar-Nathan 1998, 27; Gorin-Rosen 2000, 59-60) dating to the Late Byzantine

period (described more in Chapter 3), although no analysis has been performed on the glass. Glass vessel finds include 1025 total fragments excavated from across Bet Shean, with Umayyad dated material derived from commercial locations, including the shops built by Hisham in 738 and the Abbasid-Fatimid glass from residential buildings built above the 749 earthquake destruction layer (Hadad 2005). Hadad's report discussed stylistic and decorative change through time, as well as comparing forms with other sites. A number of imported vessels were recognised, including those most likely from Iran, Egypt and Iraq.

In Caesarea, ceramics tend to dominate publications, particularly from the Roman-Byzantine periods. A short Islamic glass report by Pollak (2003) publishes 20 drawn forms from excavations around the Temple Platform, along with another article on glass vessels from a Fatimid hoard (Pollak 2000). Limited analytical work has been performed on 25 glasses dating from the 7th to 12th centuries, as well as a mixture of waste, chunks and vessels, published in Brill (1999A & B) and Brill and Stapleton (2012).

From Sepphoris, past excavations have uncovered glass working waste dating mainly to the Late Roman and Byzantine contexts (Gorin-Rosen 2000, 57). Fischer and McCray (1999) analysed 65 samples of glass dating from 37BC to 1516 CE. They found a perseverance of natron glass into later Islamic periods. Although a summary of the excavations is published, no detail on the quantities of glass, the types or drawn forms is provided (see Strange et al 1989).

In Jerusalem, excavations of the Tyropoeon Valley (Gi'avti Parking Lot; Ben-Ami 2013) uncovered hundreds of fragments of Islamic period glass, some of which is published in Gutreich (2013). Of these, 20 diagnostic fragments are described from the Umayyad period and 22 fragments are described from the Abbasid period (8th-10th century) with parallels from Bet Shean, Ramla and Caesarea. This latter excavation closely relates to samples recovered for this project as described in Chapter 5. Further material has been published by Hadad (2003) from Temple Mount Excavations (Mazor 2003), namely 203 glass lamp fragments of two types, all of which date to approximately the late Byzantine/Umayyad periods. Limited amounts of glass have also been published from

the Cardo and Nea Church excavations dating to the 7-11th centuries (Brosh 2012, 400).

2.4.3 Military Sites - Ashdod Yam and Ha-Bonim

The sites of **Ashdod Yam** (*Azhud*) and **Ha-Bonim** (*Kafr Lam*) are two of the best preserved military installations along the Levantine coast. These two fortresses formed part of a line of 20 forts (*ribats*) that stretched 150 miles along the coast of Palestine. They functioned as coastal defences and watch stations to protect against Byzantine raids (Vunsh *et al* 2013; Khalilieh 1999) and were mainly positioned near natural harbours so that craft could dock. Ashdod Yam was located 10 miles north of Ashkelon. This fort was rectangular in plan with a number of semi-circular and square towers encompassing cisterns and store rooms (Vunsh et al 2013; Raphael 2014). The citadel was built by al-Malik (r. 695-705) in the late 7th century and abandoned after being severely damaged during an earthquake in 1033. It returned to use during the Crusader period but was once again abandoned after their expulsion in 1290. Ha-Bonim was farther north, situated 10 miles north of Caesarea and 3 miles north of Dor, on a hill half a mile from the sea. It is similarly rectangular with four projecting circular towers at the corners as well as two semi-circular towers flanking the southern entrance and strengthened by 16 buttresses. It had six vaulted store rooms opening onto a central paved courtyard, cisterns, and was built near a natural anchorage (Khalilieh 1999). Like Ashdod Yam, this fort was erected during the Umayyad period and modified during the Abbasid era; signs of neglect indicate non-defensive uses under the Crusaders until being reoccupied during the Ottoman period. It was finally abandoned in the 19th century (Barbé *et al* 2002). There are no previous glass finds or analyses apart from those of this study.

2.4.4 Rural Sites – Ahihud, Tel Rosh, Nahal Shoval

Ahihud is a small settlement 9km east of Akko, in the Western Galilee, in the north of Israel. This region was relatively densely populated during the Early Islamic period, and regional surveys have shown continued habitation of villages in the area

post-conquest, although the number of villages appear to decrease during the 8th century (Avni 2014, 212). There is little information on later periods.

Nahal Shoval and **Tel Rosh** are found at the southern area of Israel in the Northern Negev desert. This was a rich agricultural region producing wine and olive oil, although wine export declined after the conquest. Nahal Shoval was a rural settlement located north of Beersheba, along the route to Ashkelon. It was a region of dense settlements, however it underwent decline during the 7-8th century, probably due to loss of Mediterranean trade (Avni 2014, 258-9), and archaeological evidence suggests the abandonment of the rural region around Nahal Shoval during the late 9th century. Tel Rosh was another small settlement to the East of Beersheba. Whilst there is very little historical information for the site, in general, the hinterlands to the East of Beersheba saw a similar pattern as that of the north with reductions in settlement in the 7th century, and probable abandonment in the 8th or 9th century. There is little additional historical information for this site, however excavations of the small settlement of Hermeshit (Greenhut 1998) nearby provides an image of small rural settlements based on agricultural economy of wine and olive oil production. Glass has also been reported at nearby sites of Tel 'Ira (Lehrer Jacobson 1999), Horbat Liqit (Laqiyya; Gorin-Rosen 2002) and Hermeshit (Winter 1998).

Chapter 3

Byzantine and Islamic Natron Glass

3.1 Introduction

3.1.1 Glass as a Material

Glass is a set of substances which share a specific microstructure, which imparts in glass unique properties unobtainable in any other ancient material. Glass can be moulded, deformed and cut, it is also chemically inert, water resistant and can be coloured or made transparent.

Shelby defines glass as an *'amorphous solid completely lacking in long range, periodic atomic structure, and exhibiting a region of glass transformation behaviour'* (2005, 5). In a similar vein, Brill (1962, 129) specifies glass as a material that *'retains the mechanical rigidity of crystals'* but having the *'random and disordered structure of liquids'* – from this he comments that glass is more a state of matter, rather than a specific substance. Glass has also been described as a *'supercooled liquid'* (Henderson 2000, 24; Fernandez-Navarro and Villegas 2013, 3). It is this dichotomy – a solid with the atomic arrangement of a liquid – that gives glass its unique properties. Figure 3.1 illustrates this disparity; pure silica quartz demonstrates a regular repeating linear atomic structure while soda-silica glass displays a non-regular arrangement. This non-regular bonding means glass does not have a distinct melting temperature, but rather a softening range or transition temperature (Fernández-Navarro and Villegas 2013, 2). This allows glass to be shaped through manipulation, trailing, moulding or blowing (Brill 1962, 134). The softening of glass can be measured as viscosity (poise, P). At room temperature glass viscosity is 10^{19}-10^{22} P (the highest that can be measured), while at around 700°C and 10^{7} P typical Roman glass starts to deform (ibid, 136-7). Blowing or moulding would be possible at 10^{3}-10^{4} P, around 1000°C. For comparison

water at room temperature is at 0.01 P (ibid, 136). This lack of crystal structure also means glass does not have cleavage, therefore it can be cut or ground in any direction (Freestone 1991, 39). Furthermore, the absence of a rigid crystal structure creates variably sized spaces between silica rings. These can be occupied by ions of other elements. Figure 3.1 demonstrates how sodium ions are able to fill the gaps, but other ions can also be accommodated, such as cobalt, copper, manganese, and iron, which allows the glass to be coloured, decoloured and otherwise altered (ibid, 39).

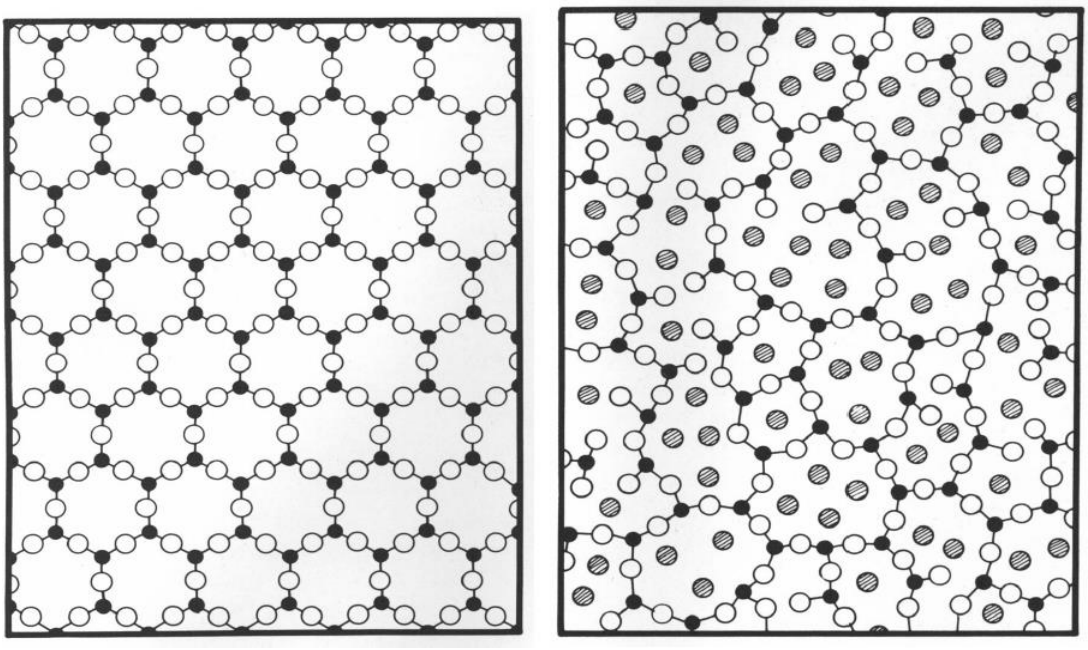


Fig 3.1. Microstructure of quartz crystals (left) and soda-silica glass (right). Note the repeating structure of the former and non-regular structure of the latter. In the glass, sodium ions are incorporated into the gaps of the silica rings (image taken from Brill 1962, 133)

Glass is made of a combination of network formers, modifiers and stabilizers. In ancient times the most common network former was silica (SiO_2), comprising approximately two-thirds of the glass by weight (Freestone 1991, 39). Due to the high melting point of silica (approximately 1700°C) a network modifier (flux) was required, which acted to reduce the melting point. This was provided by soda (Na_2O) and/or potash (K_2O), depending on raw materials, reducing the melting temperatures to around 1000°C. These raw materials alone would have produced a glass that was not chemically resistant (i.e. could dissolve), therefore an additional stabiliser was required, this was in the form of lime (calcium oxide, CaO; Hodges 1964) which made

up one-tenth of the glass, in addition, alumina and magnesia can also act in this way. Other elements are also introduced during glass manufacture, either intentionally as colourants or decolourisers, e.g. antimony, manganese, cobalt, copper, or as impurities in the raw materials, e.g. magnesium, potassium, aluminium, iron and titanium (Brems and Degryse 2014; see Section 5.5).

3.1.2 Brief Background to Ancient Glass Analysis

Volcanic glasses, such as obsidian, have been used by man since the earliest times, but from the 3rd Millennium BCE the first man-made glasses, as beads, appeared in the Near East (Freestone 1991, 38; Turner 1954, 445T). These earliest objects were generally opaque, colourful and used in jewellery, presumably to emulate semi-precious stones (Shortland 2001, 212). They were conceivably developed alongside faience and glaze making (Peltenburg 1971). It was from approximately the mid-2nd millennium BCE in Egypt and Mesopotamia that a glass vessel industry developed and glass began to appear in significant quantities (Freestone 1991, 38; Tait 2012, 22-23; Turner 1954; Sayre and Smith 1974). These first vessels were produced through coiling glass around a clay or sand core (Tait 2012, 22).

Chemical analysis is one of the key tools for understanding glass technology. From as early as the 1950s scientific analysis was used in conjunction with historical and archaeological research to investigate glass production. Early pioneers include Turner, who in a series of papers used Babylonian and Assyrian texts alongside analysis of archaeological glass and selected raw materials to identify plant ash and crushed quartz as probable ingredients of Babylonian glass (Turner 1956A, B and C). This work was followed by Sayre and Smith's seminal paper in 1961 which analysed a range of ancient glasses. They recognised two main compositional groups: high magnesia glass from 2nd millennium BCE Egypt and in 10th century CE Islamic glass; and low magnesia glass found in Roman periods (4th century BCE to the 9th century CE). This was chronologically and spatially refined in further papers (Sayre 1964, 65; Sayre and Smith 1974) which recognised a distinct divergence between Roman glass and contemporary Mesopotamian production. Through the use of Islamic coin weights they then dated

the *'re-introduction'* (Smith 1963, 288) of high magnesia glass back into former Roman territories in the mid-9th century (Sayre and Smith 1974, 65). Brill (1970, 111) concluded this work by linking this divergence to the use of plant ash as the flux source in high magnesia glass and a mineral soda, natron, in low magnesia glass.

3.2 Byzantine and Early Islamic Glass Production

3.2.1 Introduction

The Islamic conquest of Palestine in the 7th century brought no immediate recognisable shifts in material culture or craft production, including glass (Schick 1998; Walmsley 2007, 48; Milwright 2010A, 29). While new compositional types appeared during the Early Islamic period (Levantine II and Egypt II compositional groups) no notable shifts in the organisation or technologies of production have yet been recognised. It is only in the 9th-10th century, two centuries after the conquest, that major changes in technology start to emerge. This is accompanied by shifts in glass style, decorative technology, fabric quality and colour (discussed later).

Byzantine and Early Islamic natron glass production appears to adhere to the same chaîne opératoire as the Roman industry. They employed the same raw materials, principally natron as a flux and sand for the silica source, similar styles of tank furnace design, centralised production, and remained situated in the same regions of production; Egypt and Palestine. Although individual production groups came and went, the principal technologies and basic raw materials remained the same for virtually the entire of the first Millennium (up until the use of plant ash glass). Therefore, the Byzantine and Early Islamic industries cannot be discussed without first considering the Roman glass industry.

This section reviews the current understanding of natron glass production during the Byzantine period and early part of the Early Islamic period and provides an overview of natron glass manufacture. Details of changes in the later Early Islamic period and our knowledge of plant ash production will be presented in Chapter 4. Thus, this section

will start be giving a background into Roman natron glass production, providing an explanation of how the industry was organised, before examining known primary and secondary production sites and the major compositional groups so far identified during the Byzantine and Early Islamic periods.

3.2.2 Background – The Roman Glass Industry

Flux created from the ashes of halophytic plants from semi-arid and coastal areas had been the basis of glass production within Egypt and the Near East from the 2nd Millennium BCE (Brill 1970) until around the 10th century BCE, when natron began to be utilized (Schlick-Nolte and Werthmann 2003). It quickly became widespread, establishing itself as the principal flux in parts of Europe, the Mediterranean and Near East (Henderson 2013), continuing in use until around the 9th-10th centuries (Sayre and Smith 1974; Gratuze and Barrandon 1990). It was during the Roman period that glass came into its own, with production on a greater scale than anything seen before (Grose 1986). The reason for the increase in production was due to glass blowing, which appears to have been invented on the Syrian coast during the 1st century BCE (Freestone 1991; Stern 1999; Grose 1986) and quickly adopted in Italy. Glass could now be shaped much more quickly, reducing the cost of manufacture and increasing the available of glass to all levels of society for the first time (Grose 1986, 65; Stern 1999). This was accompanied by an increase in the size and efficiency of glass furnaces. Large tank furnaces were developed capable of melting many tonnes of glass on a near industrial scale (Gorin-Rosen 2000; Nenna et al 2000; Nenna 2007A; 2010).

We now have a reasonably clear understanding of the raw materials, technologies and processes of Roman glass production. Pliny the Elder, writing in 79 BCE, reported that for many centuries sand had been obtained from the mouth of the River Belus (modern Na'aman) for glassmaking (*Natural History* (Nat. Hist.) 36:65, translation in Bostock and Riley 1893). Pliny mentions the River Belus in a story detailing the first discovery of glass by soda traders (Nat. Hist. 36:65; Gorin-Rosen 2000, 49). This story is likely apocryphal but it nonetheless conveys the importance of this area to glass making. This river empties into the modern day Bay of Haifa, near the city of Akko.

Analyses of this sand (Brill 1988; 1999; Turner 1956C, 281T) has confirmed its suitability for glassmaking and matched its chemical signature to glass from a nearby late Roman glass production site at Jalame (Weinberg 1988; Brill 1988). Passages in Strabo's *Geographica* (translation Jones 1917-32) and Josephus' *Bellum Judaicum* (translation Whiston 1737) further elucidate details of the site, describing how boats would load up on the sand (Josephus 2.10.2) and transport it to Tyre and Sidon for glassmaking (Gorin-Rosen 2000, 49; Safrai 1994, 204; Strabo 16.2.25 in translation in Jones 1917-32, 273). In addition, Pliny records a second sand source at the River Volturno in Italy, but unlike the sand from the River Belus, studies have so far found it unsuitable (Silvestri et al 2006; Brems et al 2012).

For the flux, Strabo (17.1.23 in Jones 1917-32, 75) notes the collection of natron from a site near *'Momemphis'* which has been suggested as the Wadi Natrun (Lucas 1948). While Pliny also reports soda beds in Egypt near Naucratis and Memphis (Nat. Hist. 31.46), these sites have been interpreted as the lakes of al-Barnuj and Wadi Natrun (Lucas 1948). The lakes of Egypt are the only sources confirmed for glass making to date (Devulder et al 2014). For further discussions of the nature of the lakes, natron extraction and its composition, see Chapters 5 and 9.

3.2.3 Organisation of the Industry

It was at one time assumed that the Roman (and Byzantine) glass industry was similar to the pottery industry and followed an organisational model of dispersed production, with production scattered across numerous workshops (Freestone 2005; see Figure 3.2 left). Each workshop would manufacture glass from raw materials and then shape the glass into vessels. Natron would have been imported but it is expected that local sands would have been employed at each workshop. The implication of this model is that vessel composition was location specific and corresponded to the workshop that made it, although the overall recipe and technologies would be generally the same. This would also lead to a correlation between vessel form and composition. This is how the medieval European glass industry was organised (Wilmott 2005) and how the pottery industry operated. Chemical analyses have tested this

model and found that correlations between form and composition is not evident (Baxter et al 1995). While the reasons for this are disputed (Baxter et al 2005), it suggests that a dispersed production model was not in operation. A growing body of chemical data has instead demonstrated that Roman glass was made of only a few compositional groups distributed widely throughout the empire (Jackson 2005; Foster and Jackson 2009; 2010; Foy et al 2003A; Nenna et al 1997; Silvestri et al 2005; 2008; Silvestri 2008). Attempts were made to explain this homogeneity by sand processing (Silvestri et al 2006), strict recipe standardisation (Lemke 1998), large scale recycling (Baxter et al 2005; Silvestri 2008) and melt dynamics (Rehren 2000). Nonetheless, it is now generally accepted that Roman glass production followed a centralised model based on just a few primary producers.

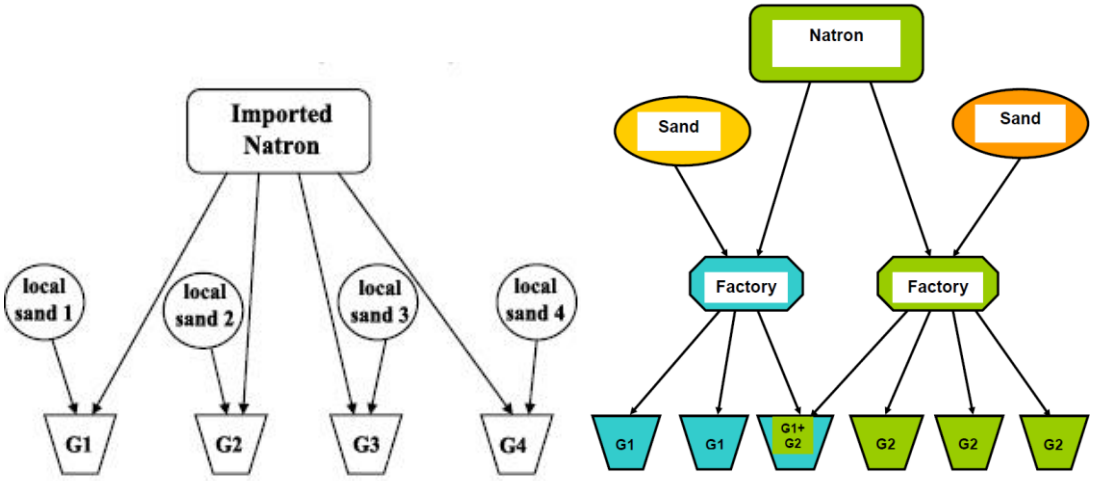


Figure 3.2. Schematic of the dispersed production model (left) and schematic of the Roman and Byzantine centralised production model (right). Both images adapted from Freestone et al (2002A).

3.2.4 The Centralised Model

In the 1960s the 'Great Glass Slab' at Bet She'arim came to the attention of glass specialists. The exceptional size of the slab at nine tonnes led Brill to suggest a centralised production model for the Roman period (Brill 1967, 95), however it was not until the published works of Nenna et al (1997) and Freestone (Freestone and Gorin-Rosen 1999; Freestone et al 2000; 2002A) that this model was brought to wider attention. Centralised production consisted of primary glass factories producing glass

from raw materials, while the vessel shaping, forming and possibly colouring was carried out at secondary sites. Primary factories would be few in number, while workshops would be widespread and more numerous (Figure 3.2 right). Primary production sites have been found archaeologically, with Egyptian furnaces having been excavated at the Wadi Natrun dating from the 1st-2nd century (Nenna et al 2003; Nenna 2007A; 2015) and sites in the region of Alexandria dating from the 1st to 8th century (Nenna et al 2000). There are also early reports of primary production from Antinoopolis, Middle Egypt, dating from approximately late Antiquity and possibly continuing later (Silvano 2015). In Israel primary production is evident at Apollonia, Bet Eli'ezer (Gorin-Rosen 1995; 2000; Tal et al 2004; discussed in detail below) and also from recently excavated furnaces at Jalame (Gorin-Rosen pers. comms.). These furnaces, holding around eight tonnes of glass, produced glass from imported natron and local sand. When cooled, the large slab was broken up into chunks and removed from the furnace. These chunks were then transported to glass workshops.

As well as the compositional evidence, there is a wealth of archaeological data attesting to the centralised model. Secondary workshops have been found across the Roman Empire, with sites in France, Britain and Israel (see overviews in Foy and Nenna 2001, Price 2005, and Gorin-Rosen 2000). A bibliography of sites in other regions can be found in Lauwers (2007, 56-7). Raw glass chunks have been found at secondary workshops (Foy and Nenna 2001; Tal et al 2008) and shipwrecks sites (Molino et al 1986; Foy and Fontaine 2007). This demonstrates the trading of raw glass over large distances. The ubiquity of workshops contrasts with the few primary production sites identified. Which are confirmed only on the Levantine coast and Egypt. Isotopic evidence hints at other production sites in the Western Mediterranean, (Degryse 2014; Ganio et al 2012A) but none have yet been discovered. Smaller scale glass making operations have been suggested at York (Jackson et al 2003), and at the Hambach Forest, Germany (Wedepohl and Baumann 2000; Wedepohl et al 2003), although primary production at the latter location has since been ruled out (Freestone et al 2009B, 44; Degryse et al 2006, 499). This lack of evidence for primary production outside Egypt and Palestine indicates that the centralised model was dominant in the Roman and Byzantine period. There are distinct advantages to such production; it

alleviates the need to ship fragile, bulky glass vessels, or the friable and water soluble natron, which possesses the added disadvantage of becoming corrosive when wet (Aerts et al 2000, 118). This organisation would also provide a more standardised glass to work with.

3.3 The Archaeological Evidence

This section will discuss the evidence for primary and secondary glass production in Palestine during the 4th-10th century. Comment will also be made on the processes and organisational characteristics of production. To aid understanding, a chaîne opératoire of natron glass manufacture has been produced in Figure 3.3. This schematic demonstrates the processes, as currently understood from archaeological and compositional investigations, showing production steps and raw materials.

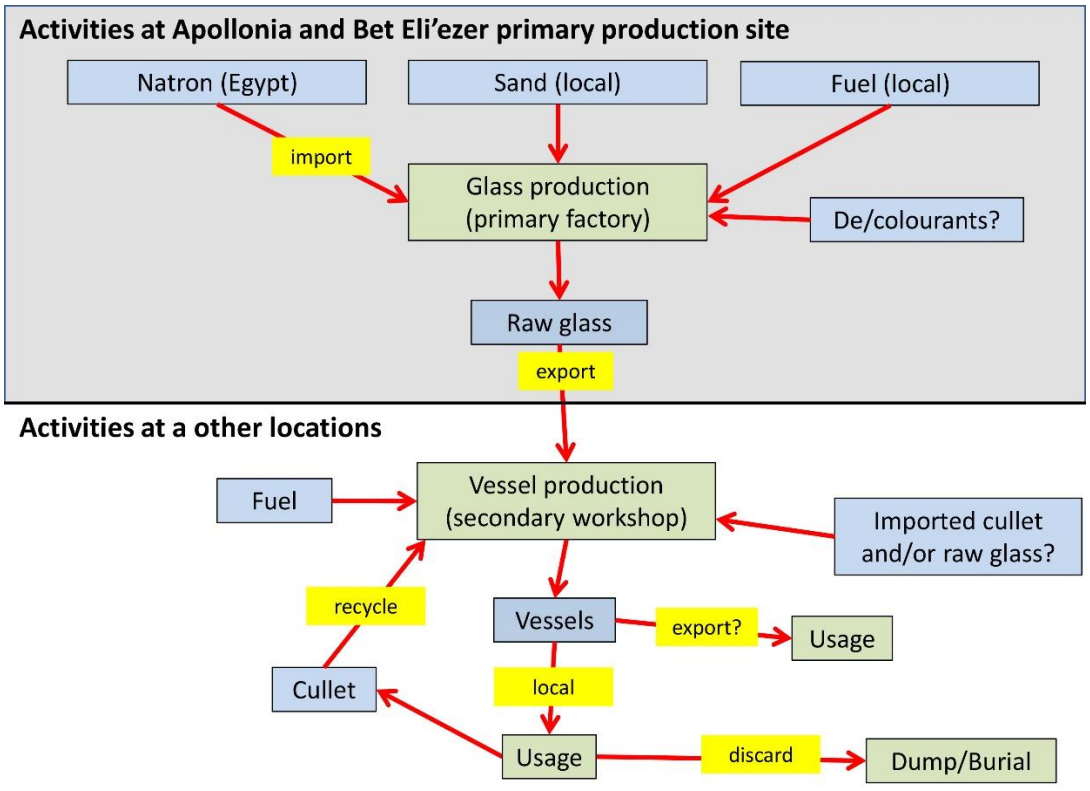


Figure 3.3. Proposed chaîne opératoire of Byzantine and Early Islamic natron glass production at Apollonia and Bet Eli'ezer (Gorin-Rosen 1995; 2000; Tal et al 2004). Raw glass production is separated from vessel shaping, which occurs at an alternative location.

3.3.1 Primary Production

Only three primary production sites have been published from Palestine dating to this time period (a 4th primary production site was recently (2015) found at Jalame and is yet to be published). The oldest are furnaces at Apollonia-Arsuf dated to the 6-7th century and located on the coast between Jaffa and Caesarea (Figure 3.4). Two furnaces were excavated in the 1950s, with further furnaces being located during excavations in 2002, giving a total of 4 furnaces (Gorin-Rosen 2000; Tal et al 2004; Freestone et al 2008A). The next site is Bet Eli'ezer, it was originally dated to the 6-7th century, but the finding of similarly composed glass from sites at 8th century Ramla suggests a later date for the production site. This site, excavated in 1992, was extensive, comprising 17 poorly preserved tank furnaces (Gorin-Rosen 1995; 2000). Surveys in area surrounding Bet Eli'ezer has found yet more glass working debris, suggesting that more furnaces were in operation and that this region formed a glass working district (Gorin-Rosen 2000, 54). The final site was Bet She'arim, alluded to earlier, which was the first tank furnace to be discovered and is famous due to its in situ glass slab.

The three sites display much similarity, with the furnaces exhibiting the same overall design. The furnaces consist of a melting chamber, measuring approximately 4m by 2-3m internal diameter, in which glass was produced as a slab with an estimated thickness of 0.25m at Apollonia (Gorin-Rosen 2000, 55), or 0.45m at Bet She'arim (Brill and Wosinski 1965). The melting chamber, recognised from the adhering glass, was normally the best-preserved part of the furnace. Attached to the melting chamber are two firing chambers (at Bet Eli'ezer), where the fuel was burnt. The furnace is a reverberatory design; hot gases being drawn into the melting chamber by a chimney at the opposite end, heating the furnace superstructure, which then radiates heat onto the surface of the glass (Figure 3.5). The capacity of these tanks has been estimated at 8-10 tonnes (Gorin-Rosen 1995, 43). An estimated 1 million vessels (at 150g each) could have been produced from the total output at Bet Eli'ezer if each furnace was fired once (Freestone et al 2000, 67).

Figure 3.4. Map showing the primary production sites of Apollonia, Bet Eli'ezer and Jalame. The site of the Wadi Natrun is also marked. The possible production areas for Egypt I, II and HIMT (in the region of Ostrakina) are also labelled in Egypt.

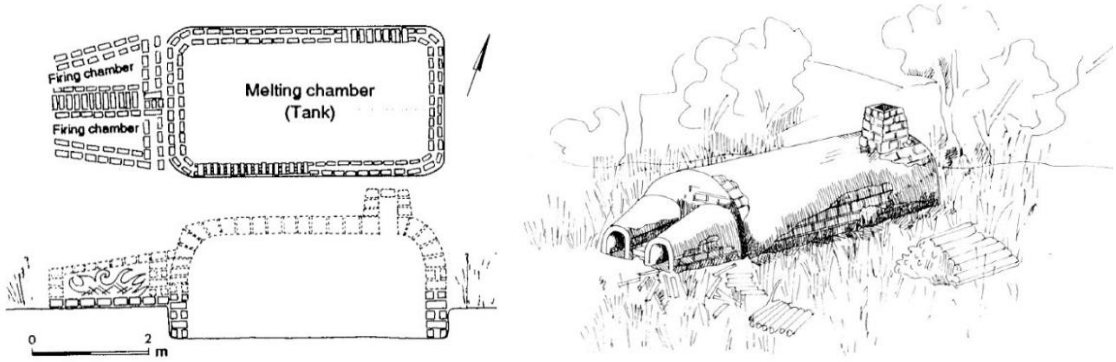


Figure 3.5 Schematic plan and reconstructed section of furnace at Bet Eli'ezer (left) taken from Gorin-Rosen (1995, 42), and an artist's impression of furnace at Bet Eli'ezer (right) taken from Gorin-Rosen (2000, 53)

Archaeological evidence, in addition to documentary sources, has given us a good understanding of certain aspects of glass production. Excavations at Apollonia and Bet Eli'ezer, as well as the weather and climate, suggests glass making to have been seasonal. The firing chambers were pointed into the prevailing wind, driving the fire, and the furnaces were therefore likely to have been fired in late summer when the winds were strongest (Gorin-Rosen 2000, 53). At Bet Eli'ezer, furnaces were probably dug in spring, when the soil was soft, while furnace construction and fuel gathering would have taken place during summer. Gorin-Rosen (1995, 43) notes that fuel was probably one of the main factors governing the siting of furnaces. Bet Eli'ezer was sited near hills that supported forests, providing fuel (Gorin-Rosen 1995, 43), while at Apollonia fuel had to be transported from farther afield (Tal et al 2004, 61). Other organic material might also have been utilized as fuel, such as reeds or waste from olive oil production. At Bet Eli'ezer the site was in use for only a short period, suggested at only a few seasons (Gorin-Rosen 2000).

Evidence suggests a single stage of production, none of the sites had evidence of open fires for fritting or charcoal preparation (Gorin-Rosen 2000, 52), nor does Pliny, in his descriptions of glass production, mention a fritting phase (Freestone 2008). Fritting is an intermediate stage where silica and flux are heated so that they sinter together, and has been evidenced in glass made during New Kingdom Egypt (Rehren and Pusch 2005). For each furnace several tonnes of raw material had to be added, probably as an already combined mixture. In the 10th century plant ash furnaces at Tyre (see Chapter 4) sequential charging is hypothesized due to layering visible in one of the discarded chunks (Aldsworth et al 2002, 64-5). This is also suggested at Bet She'arim (Brill and Wosinski 1965, 10) where unexplained layering is similarly noticeable. Sequential charging has been identified from ethnographic studies of Indian glassmaking (Sode and Kock 2001, 165) and has definite advantages in heating efficiency. Glass and its raw materials have very low thermal conductivity and as the material is only heated from one side (the top surface), it means that the heat would take a very long time to pass all the way through to the base. By charging in batches, each layer is allowed to heat and react before adding the next. This is accordingly more efficient, it takes less time and uses less fuel (Van Beeumen et al 2011). At Apollonia,

firing was estimated as taking 10-14 days for the glass to form, a further week or more for cooling, with temperatures required at around 1100°C (Gorin-Rosen 2000, 53; Tal et al 2004), although these estimates were based on the ethnographic studies of Sode and Kock (2001). After completion, the roof and side walls were likely removed to gain access to the glass. The glass was broken into chunks. Smaller pieces adhering to the floor appear to have been picked (chiselled) out leaving few remains.

The furnace at Bet She'arim is a slightly peculiar case. It is a single furnace, situated within a cave, and it retains its 9 tonne glass charge. Analysis by Brill and Wosinski (1965) quickly established the glass to be very high in lime, which raised the liquidus temperature of the melt beyond the capability of ancient glass makers, causing the formation of calcium silicate crystals. Freestone and Gorin-Rosen (1999) suggested that it was the use of plant ash flux with a typical Levantine coastal sand which resulted in the high lime composition observed. In addition, this glass contained quantities of manganese oxide, a technique that had fallen out of use in Levantine glass production of the Byzantine period but found in later Islamic plant ash glasses. They suggested this glass was the result of a merging of Islamic and Byzantine glass making traditions, and was conceivably the result of experimentation. The slab's situation strengthens the possibility of this being a secretive enterprise. The site, within an abandoned Byzantine cistern, is not accurately dated, however a 9th century period is suggested based upon the date when plant ash glass first appeared (ibid).

Work on these furnaces has identified many aspects of production, but there is little evidence for who controlled manufacture. Tal et al (2004) suggested the church had a role in glass production at Apollonia, given the influence of the church during the Byzantine period, but there is no direct evidence for this. Moreover, the church would most likely have lost authority after the conquest. Private enterprises, potentially family or clan run businesses are another possibility. Work by Kurinsky (1991) has argued for Jewish control of glass production. He doesn't provide any evidence, however, there is evidence for Jewish involvement in glass production during the 10th and 11th centuries from the Cairo Geniza (Goitein 1961, 186-189), but whether this is primary production or glass working is unclear. It is likely that glass working knowledge would have been closely guarded (Freestone et al 2008A), so family groups appear a

logical organisational structure. The idea of family enterprises sounds feasible for smaller scale Apollonia and for the experimentation at Beth She'arim, however the scale of Bet Eli'ezer with the finding of many banks of furnaces side by side, makes the idea of state organised production credible.

3.3.2 Secondary Production

Glass workshops have been found in many locations in Palestine, such as Apollonia (Freestone et al 2008) and Ramla (Tal et al 2008). A review of sites is given in Gorin-Rosen (2000), while an expanded list of identified workshops (and primary production sites) can be found through the *Revue archéologique* (search online at http://web.mae.u-paris10.fr/werre/). The most intact workshop was found at Bet Shean (Mazor and Bar-Nathan 1998; Gorin-Rosen 2000) dating to the 6th-early 7th century. It was well preserved as a result of an earthquake. It was located on a colonnaded shopping street, consisting of a front room containing a small rounded furnace with an upper melting tank and a lower firing chamber. Black ash heaps beside the furnace were interpreted as areas used for vessel annealing. These heaps contained olive pits, suggesting the utilisation of waste material from olive processing as fuel. There was an outside courtyard, and a back storeroom stacked with glass vessels ready to be sold (Gorin-Rosen 2000, 60). As with primary production, the glass producers are mainly unknown but are most likely business-owning families (Price 2005). At Bet Shean, it is noted that the range of vessels are few, signifying that this was likely local production for domestic use (Gorin-Rosen 2000 60). Most workshops are likely to have operated this way, each town having their own glass maker for local consumers, and selling either from the workshop or at local markets. As well as domestic production, Price (2005, 179) notes that glassware for commercial purposes, such as bottles for medicines, perfumes or foodstuffs, was also produced. It is expected that workshops produced most glassware for local use and the majority of vessels did not travel large distances.

Secondary furnaces formed vessels from raw glass, so that glass composition is related to the primary production. However, the way glass was worked did have an effect on

the final composition. One of these is recycling, which is attested from Roman documentary sources, as well as archaeological evidence (see references in Keller 2005). At Bet Shean, quantities of glass held in a ceramic jar and in the remains of baskets were interpreted as cullet (Gorin-Rosen 2000, 60). Recycling is likely to have been a common occurrence. Foster and Jackson (2009, 196) in a study of late Roman glass identified up to 40% of glass from some compositional groups was recycled. Recycling would be liable to cause blending of compositional groups and increase colourant elements as a consequence of mixing coloured and non-coloured glass. How this is used to recognise recycling in glass is discussed in Section 5.5.4.

In addition, contamination from fuel, either as ash falling into the melt or as vapour, has been recognised from Late Byzantine workshops, such as that at Petra, Jordan (Rehren et al 2010). Experimental work by Paynter (2008) demonstrated how potash in the glass increases over time as it is volatilised from the fuel and dissolves into the surface of the glass. Another route of contamination can come from the tank or crucible walls, although Paynter (2008) recognised no c9ontribution from the crucible in melting experiments in major and minor elements trace element level were not examined).

The writings of Pliny suggest that colourants were added at the workshop stage (Freestone 2008, 81), however analytical results do not support this. For decolourants, (manganese and antimony) addition appears to have occurred at the primary production phase as seen from the MnO content of glass chunks at Jalame (Brill 1988). The effects of colourants are discussed in Section 5.5.4.

Compositional ranges analysed from workshops are tighter than that found from primary factories. Even within a single tank furnace poor mixing and heterogeneous charging can cause compositional variation (Tal et al 2004). This was thoroughly discussed by Freestone et al (2008A) in material from a workshop site at Apollonia. Melting chunks in a workshop homogenises a glass in a manner that is not possible in a 9 tonne tank furnace. This has enabled individual batches to be identified, a batch being the result of a single melt of glass at a workshop (Freestone et al 2009A; Freestone et al 2015). This has implications for provenancing as even if individual workshops or batches can be recognised, if they fall within the range of a primary

production site, then it is likely that they would be using glass from the same site. Only if glass falls outside of this range (see Freestone et al 2015) can a new production site be considered.

As a final note, recently and for the first time glass from more than one primary production site has been identified at the same workshop from Tel Aviv, dating from the 8th to 9th century (Freestone et al 2015). This workshop contained glass of a Levantine production, Egypt II glass, and a third glass type, indicating that workshops, in some cases, bought and used raw glass from more than one source. This creates implications regarding the potential range of glass compositions possible from recycling. The appearance of more than one group increases our understanding of the complexity of glass supply and choice in the period.

3.4 Natron Glass Compositions (4th - 10th Centuries)

In a series of influential papers Freestone et al (2000; 2002A) defined five main glass production groups in circulation during the latter half of the 1st Millennium CE. The articles brought together known groups identified from a variety of articles (Foy et al 2003A; 2003B; Gratuze and Barrandon 1990; Verità 1995; Nenna et al 1997). These groups were linked to different production locations and a drive was made to understand the industry as a whole. The use of these five production groups within the centralised production model has been the framework in which glass specialists of this period have operated in for the last 15 years. However, over this time new data has supplemented this picture; the groups have expanded, sub-groups created and chronologies refined. This section will review the five production groups in terms of their definition, composition, chronology and extent, with particular attention to the Palestinian production groups. They will be discussed geographically in chronological order starting with Palestine. Lastly, details of the technology, organisation and sites of production will be discussed.

3.4.1 Production in Palestine – Levantine I and II

Production in Palestine during the Byzantine and early Islamic period is characterised by two compositional groups; Levantine I and II. Both are characterised by their pale blue 'aqua' appearance and being of high quality, particularly when compared to HIMT glass. These were first explicitly defined by Freestone et al (2000), although the Levantine I composition had been recognised in earlier work (Mirti et al 1993; Verità 1995).

Levantine I was first defined from vessels, chunks and waste glass from a 6-7th century tank furnace at the primary production site of Apollonia-Arsuf and the secondary production site at Dor by Freestone et al (2000). Glass from these sites presented similar compositional characteristics to material from 4th century Jalame, which was identified to have been made using sand from the nearby Belus River (Brill 1988). Therefore, Levantine I came to be broadly defined as a glass produced along the Levantine Coast using coastal sands similar to those from the Bay of Haifa (Freestone et al 2002A, 72). The Levantine I type, therefore, is approximately dated from the 4th to 7th century taking in the production site at Apollonia and the secondary site of Jalame. In 2002 a further tank furnace was found at Apollonia and analyses of glass chunks added to the compositional definition of this group (Tal et al 2004).

Table 3.1 presents the mean and standard deviation of the glass from Apollonia (Freestone et al 2000; Tal et al 2004) and Jalame (Brill 1988). Studying first the Apollonia data from Freestone et al (2000), the glass is seen to be a mature sand with extremely low heavy mineral elements (TiO_2, Fe_2O_3), relatively high alumina (2.9-3.4%) provided by a high feldspar fraction, significant lime content (6.2-10.3%), relatively high soda (14.2-17.0%) and mid-levels of silica (67.4-73.3%). CaO/SrO correlation and strontium isotope studies have confirmed the use of coastal sand with lime contributed by shell fragments rather than limestone (Freestone et al 2003; Freestone 2006). The additional analyses from Apollonia (Tal et al 2004) acted to expand the composition range, pushing soda and silica averages lower and higher respectively, but showing very close similarity in all other elements. Figure 3.6 displaying CaO/Al_2O_3 against Na_2O/SiO_2 plots these data alongside that from Jalame and Bet Eli'ezer. The

Table 3.1. Average (bold) and standard deviation (italics) compositional data for Levantine production; Levantine I is represented by the data from primary production sites of Apollonia and secondary site of Jalame, and Levantine II by data from Bet Eli'ezer. Data sources shown. Values are wt %. N = number of samples.

	N	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Fe_2O_3
Apollonia (Freestone et al 2000)	**9**	**15.18**	**0.63**	**3.06**	**70.71**	**<0.10**	**0.30**	**0.84**	**0.72**	**8.08**	**n/a**	**0.47**
Stdev		*0.86*	*0.09*	*0.16*	*1.87*	*n/a*	*0.09*	*0.10*	*0.33*	*1.50*	*n/a*	*0.13*
Apollonia (Tal et al 2004)	**14**	**13.65**	**0.63**	**3.38**	**71.97**	**0.05**	**0.10**	**0.84**	**0.52**	**8.29**	**n/a**	**0.46**
Stdev		*1.12*	*0.20*	*0.14*	*1.55*	*0.01*	*0.05*	*0.08*	*0.14*	*0.86*	*n/a*	*0.05*
Jalame (Brill 1988)	**26**	**15.74**	**0.58**	**2.74**	**69.74**	**n/a**	**n/a**	**n/a**	**0.78**	**8.69**	**0.09**	**0.46**
Stdev		*0.91*	*0.13*	*0.15*	*1.61*	*n/a*	*n/a*	*n/a*	*0.13*	*0.64*	*0.01*	*0.21*
Bet Eli'ezer (Freestone et al 2000)	**52**	**12.12**	**0.63**	**3.32**	**74.89**	**<0.1**	**0.17**	**0.64**	**0.46**	**7.16**	**<0.1**	**0.58**
Stdev		*1.32*	*0.09*	*0.28*	*1.48*	*n/a*	*0.06*	*0.13*	*0.08*	*0.60*	*n/a*	*0.22*

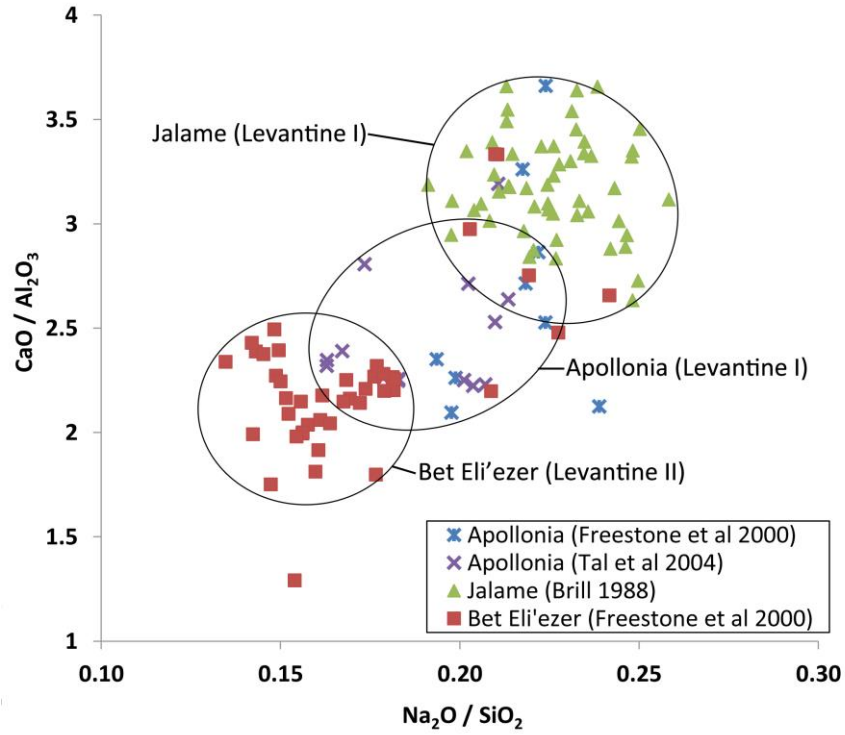


Figure 3.6. Graph comparing glass compositions from the primary production sites of Apollonia, Jalame and Bet Eli'ezer. Circles mark the principal regions for each production group, demonstrating distinctive differences.

results from Apollonia are shown to be quite variable, much more so than that from secondary sites (e.g. Apollonia and Ramla, Fig 3.7; Freestone et al 2008A, 75). This high variability is probably due to poor mixing within the tank and divergences due to charging (Freestone et al 2000, 71). The material from Jalame is similar to that from Apollonia, but with some variation seen in the alumina and lime levels, lower and higher respectively. This indicates a different calcite/feldspar mix in the sand, implying an alternative sand source and production site. These differences suggest that it is possible to distinguish distinct sand sources and production sites along the coast.

The Levantine II group is defined from 27 glass samples taken from 4 furnaces at the primary production site of Bet Eli'ezer. Levantine II, like Levantine I, was made using a mature coastal sand high in alumina and lime. Compositional ranges of accessory mineral elements are extremely similar showing close affinity in the sands, however alumina average and range is slightly higher (2.7-4.2%) and lime lower (6.0-7.9%). Most

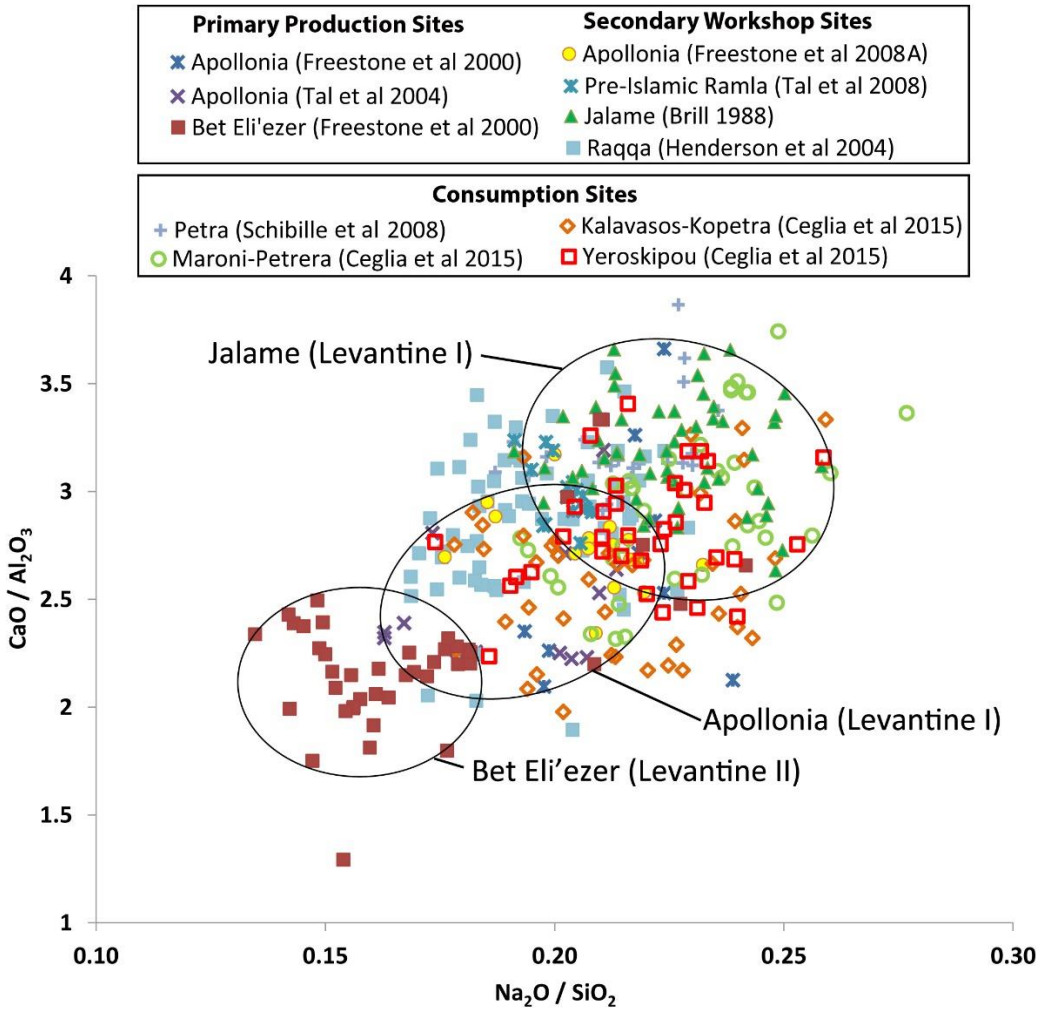


Figure 3.7. The primary production sites of Figure 3.6 with additional Levantine data from various secondary production and consumption sites. This image suggests that regionally characterised sub-types within Levantine glass might be recognisable, these include Bet Eli'ezer production, but also distinctions between Apollonia, Jalame and, possibly, Raqqa Type 3.

importantly for distinguishing these groups, Freestone et al (2000) noticed distinctly higher silica (72.1-76.0%) and lower soda (10.9-16.1%) in the glass from Bet Eli'ezer. This was explained by recipe change and a reduction in the amount of natron added to the sand. The lowering of the soda content increased the melting temperature of the glass and also made it stiffer to work, and so it was reasoned that this change was a deliberate choice, possibly as a way of conserving natron (ibid, 72). This difference is evident in Figure 3.6, pushing the Bet Eli'ezer samples to the left of the graph. On the whole soda/silica and lime/alumina is able to separate Levantine I and II, but it should be noted, that there is a partial overlap between analyses from Bet Eli'ezer and Apollonia.

Table 3.2. List of sites containing Levantine I and II type glass.

Reference	Location	Date	Site	Material	Number	Method	Type
Israel							
Freestone et al 2000	Apollonia	6-7th century	primary	chunks, vessels	9	SEM-EDX	Lev I
Tal et al 2004	Apollonia	6-7th century	primary	chunks	14	EPMA	Lev I
Freestone et al 2008	Apollonia	Late Byzantine	secondary	chunks, vessels	16	EPMA	Lev I
Freestone et al 2000	Dor	6-7th century	secondary	chunks, vessels	12	SEM-EDX	Lev I
Brill 1988	Jalame	4th century	primary?	chunks, vessels	57	SEM-EDX	Lev I
Tal et al 2008	Pre-Islamic Ramla	6-7th century	secondary	chunks, vessels, waste	16	SEM-EDX	Lev I
Freestone et al 2000	Bet Eli'ezer	6-8th century	primary	chunks	27	SEM-EDX	Lev II
Freestone et al 2015	Tel Aviv	8th century	secondary	vessels, waste, chunks	13	EPMA	Lev II
Cyprus							
Freestone et al 2002A	Maroni Petrera, Cyprus	6-7th century	consumption	vessels	14	SEM-EDX/ solution ICP	Lev I
Ceglia et al 2015	Yeroskipou, Maroni-Petrera and Kalavasos-Kopetra, Cyprus	5-7th	consumption	vessels	115	EPMA	Lev I
Jordan, Lebanon and Syria							
Schibille et al 2008	Petra Church, Jordan	5-7th century	consumption	window glass	23	WDS	Lev I
Rehren et al 2010	Petra Church, North Ridge Church, Deir Ain Abata, Christian Monastery, Jordan	5-7th, 5-6th and 4th-8th	consumption	vessels and windows	70	WDS	Lev I
Abd Allah 2010	Biet Ras/Capitolias, Jordan	3-6th century	secondary	raw glass and vessels	40	AAS	Lev I
Al-Bashaireh et al 2016	Umm el-Jimal, Jordan	7th century	consumption	vessels	15 4	EPMA	Lev I Lev II
Henderson 2013	Bierut, Lebanon	1st C AD	primary		?	?	Lev I??
Henderson et al 2004	Tel Zujaj, Raqqa, Syria	8-9th	primary and secondary	vessels, chunks, waste	61	WDS	Raqqa Type 3 = Lev I?

Table 3.2 continued…

Italy							
Verita 1995	Rome, Italy	4-6th century	consumption	vessel	13		Levantine I
Silvestri et al 2005	Grado, Italy	7th century	consumption	vessel	6	XRF and EPMA	A/GRA = Lev I
Silvestri et al 2006	Iulia Felix, Pozzuoli and Vicenza, Italy	Roman? to 9th century	consumption and shipwreck	vessel and cullet			A2/1 = Lev I?
Egypt							
Freestone et al 2002B	North Sinai, Egypt	4-5th century	consumption	vessel	10	SEM-EDX	Lev I??
Kato et al 2009	Raya and Wadi al-Tur, South Sinai, Egypt	7-8th century	consumption	vessels	25	pXRF	Lev II (but could be Lev I?)
Various locations							
Foy et al 2003	France, Tunisia, Libya, Egypt, Levant, Lebanon	4-5th, 5-6th and 7-8th	consumption	vessel, window, raw glass and waste	123	ICP-MS	Groups 3.1, 3.2 and 3.3 = Lev I
Foster and Jackson 2009	Various sites, Britain	4th century	consumption	vessels	24		Lev I

This is particularly apparent when using the Tal et al (2004) data. Furthermore, there are, as mentioned, differences between the glass from Jalame and Apollonia showing that at least two, and possibly more production sites within the Levantine I group. As will be seen, these characteristics are somewhat problematic when attempting to assign analysed vessels to a particular group.

Finally, note that Schibille et al (2016) in a recent article reported a high magnesia sub-group within Apollonian glass production which was first recognised by Tal et al (2008). It was suggested that this was caused by a slightly different sand mineral mixture, although other oxides mainly remain the same. This, therefore, presents a further sub-type within Levantine I.

3.4.2 Spatial and Chronological Extent

A wide distribution of Levantine I glass across the Empire is apparent in the early Byzantine period but contracts in later centuries. Levantine II, on the other hand, is rarely found and is much more restricted in extent. Table 3.2 lists sites containing Levantine I and II with number of analyses, date, type and reference. Data from a selection of these sites are plotted in Figure 3.7. The aim of this section is to understand the chronology, spread and compositional variation of the Levantine I and II groups. This is not an exhaustive list but does aim to include all the major finds.

Levantine I is a widespread and ubiquitous glass type. Table 3.2 refers to 707 samples from 22 articles and 11 countries ranging from Israel and Jordan (Freestone et al 2008A; Rehren et al 2010; Schibille et al 2008), Italy (Silvestri et al 2005; Silvestri 2008; Verità 1995), Egypt (Freestone et al 2002B), Cyprus (Ceglia et al 2015; Freestone et al 2002A), as well as various locations in France and North Africa (Foy et al 2003A) and sites in Britain (Foster and Jackson 2009). Although it must be noted that despite this wide range, Levantine I does not appear to have been as extensively distributed or abundant as HIMT.

The dating of the Levantine I glass is quite consistent. During earlier periods Levantine I is found across the Mediterranean and at sites in Northern Europe (Foster and Jackson 2009; Foy et al 2003A), however in the 5th and 6th centuries it becomes more restricted

to sites in the Eastern Mediterranean (Ceglia et al 2015; Freestone et al 2002A; 2002B). The majority of articles date Levantine I glass to the 4th-7th centuries, this corresponds with known primary production at 4th century Jalame and that from 6th-7th century Apollonia, although presenting chronological gaps in production during the 5th century inferring as yet unknown production sites.

In general, Figure 3.7 shows close correspondence between the Levantine I glass from the separate locations. We have already mentioned differences between Apollonian and Jalame production, but any additional variation also might suggest chronological differences. The glass from 4th century Jalame and some of the 5th-7th century material from Maroni-Petrera, Cyprus, has a relatively high CaO/Al_2O_3 ratio. This contrasts with glass from 6-7th century Apollonia and Kalavasos-Kopetra, Cyprus, with lower CaO/Al_2O_3 ratios. This implies changing sand sources and/or production sites. This trend towards lower CaO/Al_2O_3 ratio over time is not shared by the 8/9th century glass from Raqqa however. In terms of soda/silica ratio, no strong overall trend is evident with the exception of production from Bet Eli'ezer, although the ratio in the Raqqa glass is also quite low. Chronological variation was reported by Foy et al (2003A). In their study of 123 samples of Levantine glass, they were grouped into three sub-types (within Group 3) dating 4th-5th, 5th-6th and 7th-8th. This work highlights one of the potential drawbacks of Levantine I as a term, that its use hides additional variation which might inform on further production sites.

While most glass assigned to the Levantine I group dates from the 4th to 7th centuries, there are some other examples which potentially fit the compositional characteristics. Silvestri et al (2005) does not separate Levantine I from typical Roman blue-green glass in her study of glass from Italy, therefore suggesting Levantine I production from the 1st century CE. Furthermore, glass of a Levantine I composition type has been described, but not fully published, from a primary production site at Beirut dating from the 1st century BCE to 1st century CE (Henderson 2013, 242). Levantine I glass has also been identified from late 8th-early 9th century Raqqa (Henderson 1999; Henderson 2003A, 113; Henderson et al 2005B) with a further chunk found dating to the 11th century (Henderson et al 2004). The latter date is late for natron glass production

(discussed later). These findings suggest a trade of raw glass to Raqqa from Palestine during the Islamic period.

Levantine II is a rarer glass, much more constrained in its spatial and chronological extent. As well as the site of Bet Eli'ezer (Freestone et al 2000), samples are noted from Tel Aviv (Freestone et al 2015) and Ramla (Freestone et al 2000 but data is not published). A possible single sample has been identified from Southern Jordan (Rehren et al 2010), dating up to the 8th century, and 4 potential samples are reported from 7th century Umm el-Jimal (Al-Bashaireh et al 2016). The only major find of this glass type is from Raya, South Sinai (Kato et al 2009) with their N1 group of 25 pale-greenish to blue glass samples reported as Levantine II. This glass dates to the 8th century and disappears in 9th century contexts, suggesting a cessation in production at this time (Shindo 2007, 100). However, the published data does not justify this identification as neither silica nor soda are measured, these are the only elements that can distinguish Levantine II from I. The data from Raya is therefore inconclusive for Levantine II. The general absence of Levantine II has a number of explanations; i) a lack of excavations for the relevant time periods is still a problem; ii) possible overlap between the groups meaning that Levantine II glass might in some circumstances not be recognised; iii) alternatively, this type may have had smaller production runs over a much shorter time period, despite the large scale enterprise seen at Bet Eli'ezer. Therefore, this glass would have limited impact on the wider region.

In this evaluation of Levantine production some issues become apparent. Chiefly among these is that Levantine I is overly large in its remit and encompasses a series of potentially separate production groups operating over time, but centred along the Levantine coast. Recognising differences between individual production sites through the analysis of vessel glass is potentially possible but also fraught with difficulty. A second issue is that material analysed from the production sites of Apollonia and Bet Eli'ezer overlap in part, principally due to variations in waste from production sites, and much less so in material from secondary production sites. Nonetheless, as the distinctions between these compositions are so fine, care must be taken in assigning glasses of these groups.

In this thesis, due to the distinct compositional differences identifiable between the samples from Jalame, Apollonia and Bet Eli'ezer, the terms Levantine I and II will be replaced by compositional group names based on those production sites, for example, Apollonia-type glass. Thus results of this project will be compared to these production types rather than the Levantine I group as a whole. This will enable differences in Levantine production to be better represented and distinctions more clearly identified between compositional types.

3.4.3 Production in Egypt – HIMT, Egypt I and II

As the sole producer of natron, Egypt had a long history of glass production. It was a major manufacturer of glass during the Roman, Byzantine and Islamic periods. Three main compositional groups have been attributed to Egypt during this period; HIMT, Egypt I and Egypt II. Table 3.3 contains the average and standard deviations of a selection of sites that have been used to define these groups.

3.4.3.1 HIMT

HIMT stands for high iron, manganese and titanium, a type dating from the 4th to 6th-7th century. This group is marginally outside the date range of the present project but its importance merits its discussion. This term was first coined by Freestone (1994, 290) from analysis of raw glass from late Roman Carthage. This glass is a distinctive greenish-yellow and sometimes olive in colour. In more recent years a number of variants and sub-groups have been recognised within this type. An excellent recent discussion and evaluation of HIMT is published by Nenna (2014) and additional details of the interplay between 'weak' and 'strong' HIMT variants and dating is given in Foster and Jackson (2009), Ceglia et al (2015) and Rosenow and Rehren (2014), and so will not be discussed in detail here.

The main characteristics of this glass type are the high levels of iron (~2-3%), manganese (~2%) and titania (~0.5%), in addition this glass type has significant amounts of soda (~17-19%). Analytical work by Freestone et al (2002B; 2005; 2009B) identified HIMT to consist of two components; a sand high in FeO, TiO_2, Al_2O_3 and MgO, indicated by the strong inter-correlation between these elements, and a

Table 3.3. Average (bold) and standard deviation (italics) data of HIMT, Egypt I and Egypt II types from various sites. All data as weight % except ZrO_2 as ppm where available. N = number of samples.

	Type	N	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO	ZrO_2
Bubastis (Rosenow and Rehren 2014)	HIMT	28	**18.1**	**1.0**	**2.7**	**64.8**	**0.1**	**0.3**	**1.0**	**0.4**	**5.7**	**0.5**	**2.0**	**2.0**	**n/a**
StDev			*1.1*	*0.1*	*0.2*	*1.6*	*0.0*	*0.1*	*0.1*	*0.1*	*0.5*	*0.1*	*0.8*	*0.4*	*n/a*
Carthage (Freestone 1994)	HIMT	3	**17.5**	**1.2**	**3.1**	**64.2**	**n/a**	**0.2**	**1.0**	**0.4**	**5.6**	**0.6**	**2.7**	**2.3**	**n/a**
StDev			*1.6*	*0.1*	*0.3*	*0.6*	*n/a*	*0.1*	*0.1*	*0.1*	*0.8*	*0.1*	*0.8*	*0.6*	*n/a*
North Sinai (Freestone et al 2002B)	HIMT	13	**17.9**	**1.0**	**2.9**	**65.3**	**n/a**	**0.4**	**1.0**	**0.5**	**5.7**	**0.5**	**1.9**	**2.5**	**n/a**
StDev			*1.0*	*0.2*	*0.2*	*1.0*	*n/a*	*0.1*	*0.1*	*0.1*	*0.5*	*0.1*	*0.8*	*1.2*	*n/a*
Fustat (Gratuze and Barrandon 1990)	Egypt I	24	**18.2**	**0.9**	**4.1**	**70.0**	**n/a**	**n/a**	**0.9**	**0.4**	**3.0**	**0.5**	**1.7**	**0.1**	**246**
StDev			*1.4*	*0.1*	*0.3*	*1.2*	*n/a*	*n/a*	*0.1*	*0.1*	*0.2*	*0.1*	*0.3*	*0.0*	*65*
Fustat (Gratuze and Barrandon 1990)	Egypt II	15	**17.3**	**0.6**	**2.2**	**67.9**	**n/a**	**n/a**	**1.1**	**0.3**	**9.3**	**0.3**	**1.0**	**0.0**	**220**
StDev			*2.0*	*0.1*	*0.4*	*1.9*	*n/a*	*n/a*	*0.2*	*0.2*	*1.3*	*0.1*	*0.2*	*0.0*	*80*
El Ashmunein (Bimson and Freestone 1985)	Egypt II	4	**15.0**	**0.5**	**2.1**	**68.2**	**n/a**	**n/a**	**1.1**	**0.2**	**10.8**	**0.3**	**0.8**	**b.d**	**n/a**
StDev			*0.3*	*0.2*	*0.4*	*1.3*	*n/a*	*n/a*	*0.1*	*0.1*	*1.4*	*0.0*	*0.2*	*b.d*	*n/a*

separate component high in CaO. Lead and strontium isotopes implied an inland sand for the former, and a coastal sand for the latter (Freestone et al 2005, 154), while the Mn was added separately, probably to prevent the formation of iron sulphide compounds in the glass (ibid, 155). Foy et al 2003A suggested that HIMT came from Egypt due to the high titania in the glass, which was typical to other Egyptian glasses, as well as the considerable quantities of soda. In addition, the complicated geology of North Sinai allows the existence of marine sands and sands with a terrigenous component together. Nd isotope results for HIMT glass present ranges within the boundary of Egypt (Freestone et al 2009B), with recent articles suggesting the site of Ostrakina, North Sinai, as a potential production site (Nenna 2014, 188).

HIMT is a broad group, identified from many sites across the Mediterranean and Roman provinces; North Africa (Freestone 1994; Foy et al 2003A); Cyprus (Ceglia et al 2015), Britain (Foster and Jackson 2009); Italy (Mirti et al 1993; Silvestri 2008), and Egypt (Rosenow and Rehren 2014; Freestone et al 2002B; Foy et al 2003A). Use of HIMT extends from around the 4th century to the end of the 7th century (Nenna 2014, 186). HIMT was contemporary to Levantine I production and on the whole more abundant and wide ranging. The reasons for this have been discussed and it was concluded that HIMT was probably a cheaper glass (Foster and Jackson 2009; Nenna 2014, 186). It is more strongly coloured and tended to have a poorer fabric with more black specks. In Britain there is evidence for HIMT being used for utilitarian and lower status vessels, while Levantine I was utilised for higher quality glassware (Jackson and Foster 2014, 12). In addition, it has higher soda content than Levantine I which would have lowered the melting temperature and thus cut working costs.

HIMT has recognised variants termed ‘strong’ and ‘weak’. Foy et al (2003A) split HIMT into Groups 1 and 2, the ‘stronger’ of these containing higher quantities of the diagnostic elements iron, manganese and titania dated earlier, to the 5th century. While the ‘weaker’ glass dated to the 6th-7th centuries. Rosenow and Rehren (2014) alternatively date their stronger varieties to the 4th-6th centuries. The glass analysed in Freestone (1994; Freestone et al 2002B) more closely corresponds with the ‘strong’ variety. Work by Foster and Jackson (2009) on glass dating to the 4th century also

recognised two varieties. Further HIMT variants include HLIMT with high lime (Ceglia et al 2015) and HIT, without manganese (Rehren and Cholakova 2010).

Table 3.3 presents average and standard deviation HIMT data from Late Roman Carthage, Tunisia, 4th-5th century North Sinai and 4th-6th century samples from Bubastis of which only the 'strong' HIMT types are represented, selected due to their later dating.

3.4.3.2 Egypt I

The Egypt I group is a rare but distinctive compositional group. The term was coined by Freestone et al (2000) but it was first identified as 24 samples of group 1A and 1B in Gratuze and Barrandon (1990) from weight standards excavated from Fustat. Stamped with the mark of the ruling official at the time, these objects can be well dated to 712-790 CE.

Egypt I (Table 3.3) is characterised by very low lime (av. 3%), high alumina (av. 4.05%), and, as shared by Egyptian natron glass in general, relatively high quantities of elements associated with some of the heavier accessory minerals; av. 1.74% iron oxide, 0.5% titania, 246ppm zirconia and ~500ppm manganese oxide. Soda levels, again typical of Egyptian glasses, are high, av. 18.25%. The names of Egyptian officials on the weights suggest an Egyptian production location. This is supported by the high zirconia and titania already noted in Egyptian glass (Nenna 2014; Foy et al 2003B, 141). Freestone et al (2000, 72) reported the similarity of Egypt I to glass waste analysed by Sayre and Smith (1974, 61) attributed to factories in the Wadi Natrun, Egypt, and vessels with low lime, high alumina compositions have also been found dating to the Roman period (Picon et al 2008). However, no furnaces dating to this period have yet been excavated (Nenna et al 2005; Nenna 2014) and so production here cannot be confirmed.

Egypt I is a rare group with few occurrences at present. Foy et al (2003B) analysing glass from Tebtynis and Fustat matched 28 samples of their Groups 8 and 9 to Egypt I, the samples date to the Umayyad period (mid-7th to mid-8th). A further 11 samples were identified at Raya, as Kato et al's (2009) group N2-a2, a group of green coloured glass dating to the 8th century. Ceglia et al (2015) reports the only fully confirmed

instance of Egypt I outside Egypt with 5 samples from the sites of Yeroskipou and Kalavasos, Cyprus, dating to the first half of the 7th century, somewhat earlier than other sites. They note that these were particularly superior quality green glass fabrics, and suggested that the objects were imported specially. There is also a noticeable absence of Egypt I glass from Bubastis, a site in close proximity to the Wadi Natrun (Rosenow and Rehren 2014, 182). However, as these samples date up to the 6th century, this absence supports a later 7th-8th century dating as implied by the other find sites.

3.4.3.3 Egypt II

The final natron glass type is that of Egypt II. This group is defined by material sourced from two locations. The first, as with Egypt I, are 15 samples of Islamic coin weights from Fustat as identified as Group 2 in Gratuze and Barrandon (1990) and dated to the 8th and 9th century (785-870 CE). The second was a secondary workshop at Tel el Ashmunein, Middle Egypt, which yielded 3 vessels and 1 raw glass chunk of similar composition (Bimson and Freestone 1985), these were tentatively dated to around the 7th century, although one vessel was thought earlier, 5th/6th century (ibid 241).

Egypt II is characterised (Table 3.3) by high lime levels (9-10%) and low alumina (~2 %). The relatively high quantities of the heavier accessory mineral elements (~1% iron oxide, ~0.2% titania and ~220ppm zirconia) is typical of Egyptian glasses but lower than Egypt I and HIMT. One particular characteristic that sets Egypt II apart from the other glasses is the reduced amounts of strontium, which does not correlate with the lime content. Although the production site is not known, the low Sr abundance and isotopic signature (Freestone et al 2003) suggest an inland sand with calcium provided by limestone, not shell.

This production group is more common than Egypt I, although still less frequent than HIMT and Levantine I. 18 samples of Foy et al's Group 7 (2003B) were identified as a Egypt II composition, dating to the Abbasid period, 8-9th century (ibid, 141). The largest collection of Egypt II has been found from Raya (Kato et al 2009). Their N2-b group accounted for 61 samples and dated to the 8th to late 9th century. This is a surprising quantity of material considering the lack of finds from other sites so far. This could be due to a confined spatial distribution of Egypt II, or to a lack of excavations for this

time period at other sites. Kato et al (2009, 1706) states that samples of this glass type include manganese decolourised and cobalt coloured examples, this latter group also has increased iron.

The potential importance of Egypt II as a later production group is suggested by the finding of this glass type at Ramla, dating to the 8-9th century (Freestone et al 2000, 73; data not published). Most recently, raw glass of Egypt II composition has been found from the late 8th century secondary workshop at Tel Aviv (Freestone et al 2015). This indicates a trade in Egyptian glass to Palestine; currently a unique occurrence as Palestinian sites tend to be dominated by local production. A further 4 or 5 possible Egypt II samples have been identified from Southern Jordan, principally Deir Ain Abata Monastery dating to the 8th century (Rehren et al 2010). The remaining assemblage from the sites were overwhelmingly Palestinian in origin.

Chapter 4

Islamic Plant Ash Glass

4.1 The Route to 'Islamic' Glass

Work by Lamm (1928; 1929-30; 1935) on the glass from Samarra and Susa, Iraq, was an important early start in the study of Islamic glass. However, for a number of reasons the study of Islamic glass has lagged behind Roman and Byzantine research. In the last 20 years there has been an upsurge in interest due to several important Islamic period excavations, which have resulted in significant books, articles and monographs. Israel, in particular, has produced notable glass reports from Bet Shean (Hadad 1998; 2000; 2005; Katsnelson 2014), Ramla (Gorin-Rosen 2010A; Pollak 2005; 2007), Tiberias (Lester 2004A; Hadad 2008), Yoqneᶜam (Lester 1996), Hammat Gader (Lester 1997) and Caesarea (Pollak 2000; 2003). Further glass reports from Israel can be accessed from the publications of *'Aliqot* and *Hadashot – Excavations and Surveys in Israel*, both produced by the Israel Antiquities Authority. These accounts are primarily typological and stylistic investigations and have, in recent years, built up a valuable chronology of the development of Islamic glass. Hadad's (2005) study of Bet Shean also highlighted the importance of regionalism in glass types (also discussed by O'Hea (2003) using material from Pella, Jordan) an issue that is commonly overlooked. Significant recent studies from outside Israel include work from Fustat (Scanlon and Pinder-Wilson 2001; Kawatoko and Shindo 2010) and Raya (Kawatoko 2007; Shindo 2005; 2007) in Egypt, Nishapur, in Iran (Kröger 1995), Pella in Lebanon (O'Hea 2003) and the Fatimid period Serçe Limanı shipwreck (Bass et al 2009) off the coast of Turkey.

Museum collections provide another source of data. Influential works dealing with developments in Islamic glass include the Eliahi Dobkin Collection from Israel (Israeli 2003), the Islamic glass published by Brosh (2003), the Al-Sabah Collection, Kuwait, published by Carboni (2001) and finally the glass from the Metropolitan Museum and

the Corning Museum of glass, published by Carboni and Whitehouse (2001). These works discuss the main decorative types, as well as the dating and potential origins of the techniques, although there is still much debate about the origins of certain types.

4.1.1 Glass in the Late Byzantine-Umayyad Period

As discussed earlier, it is generally now acknowledged that the Islamic conquest had little immediate impact on the material culture of the 7th century (Avni 2014; Milwright 2010A; Walmsley 2007). There was '*little impact on glass-working'* (Brosh 2003, 319) and a *'direct continuation'* of craft traditions (Pollak 2003, 165). The conquest provides no event horizon in glass production (Carboni 2001, 15) with Syro-Palestine continuing to use classical Byzantine styled glass and Mesopotamian glass following Parthian-Sasanian traditions (Pollak 2003, 165). Nevertheless, the conquest set in motion changes that would have a large and lasting impact on glass, along with other material culture. Regions once separated by war and culture were unified under a single rule and language, thereby encouraging and facilitating the movement of people, trade and the spread of traditions and knowledge.

The mid-Umayyad period saw some of the first expressions of Islamic identity. This is demonstrated in the first Islamic monumental constructions and new architectural styles, e.g. the Dome of the Rock (completed 692), Al-Asqa Mosque (705) and Great Mosque of Damascus (715; Brosh 2003, 323; Milwright 2010A, 25; 2010B; Johns 2003). However, the use of coloured window glass and mosaics in these buildings (Brosh 2003, 322), as well as the continued use of Byzantine forms such as wine goblets and decorative techniques of trailed, pinched and mould blown designs, demonstrates adherence to Byzantine practices in glass production and taste, and a slow uptake of glass as a medium for Islamic cultural expression. Carboni identifies two potential reasons for this: a lack of patronage from the new Islamic elite and/or that Jewish artisans in the glass industry might have been slower to convert (Carboni 2001, 15).

It was during the late 7th and early 8th centuries, during the reigns of al-Malik (r. 685-705) and al-Walid (705-15), that changes in vessel styles are first recognised (Brosh 2003, 333; Hadad 2005, 78). Carboni (2001, 15) calls this glass *'proto-Islamic"*, as these

vessels still lacked the shapes defined as '*Islamic*' style which were to come later. Nonetheless, the vessels revealed new forms, with globular, elongated bodies and thick bases. Concurrently, the vessel fabrics became rather less refined, containing bubbles and "*black grit*", and with the vessels themselves often *'carelessly executed and frequently asymmetrical'* (Brosh 2003, 333).

4.1.2 The Abbasid Period and the 'New Islamic Style'

It is under the Abbasid caliphate from around the late 8th- early 9th century that a stylistically and technically distinct Islamic glass appears (Brosh 2003, 319-20; Gorin-Rosen 2010A, 214). The new styles were created out of a fusion of Classical-Byzantine and Parthian-Sasanian traditions. Most of the decorative techniques that came to define Islamic glass were reused or revived from previous periods, but finding new form at this time. The development of Islamic styles in glass came via a number of potential mechanisms. One was the opening up of Byzantine and Sasanian territories to free movement and trade, thereby allowing the transfer of ideas between previously isolated regions. This knowledge transfer was accelerated by the movement during the Abbasid period of the capital from Damascus to Baghdad (Shindo 2007, 97), which increased the intensity of East-West trade and the movement of people, traders and craftsmen. Furthermore, new city construction at Baghdad (founded 761) and Samarra (founded 838; Brosh 2003, 323; Carboni 2001, 15), and the formation of industrial districts outside major cities, like those at Raqqa, Basra and Fustat (Heidemann 2006; Milwright 2010A) created concentrated clusters of craft workers gathered from across the caliphate. The intermingling of workers from various regions would have encouraged the transfer of knowledge, but probably also increased levels of innovation through the exchange of ideas between artisans from different industries, as well spurring innovation through competition. These changes would have acted to encourage technological innovation and the pace of adoption of new technology during the Abbasid period.

Carboni (2001, 16) attributes the strongest influence on new Islamic typologies to Roman traditions, characterised by decorative techniques such as applied trails and

mould blown glass, particularly with vertical ribbing. A smaller contribution is placed upon Sasanian traditions (ibid), although facet and wheel-cut decorations, particularly characteristic of Sasanian glass, became very popular during the 8th-10th centuries, while relief cut techniques reached their height a little later during the 10th and 11th centuries (ibid, 5). Movement of craftsmen around the Empire allowed these new techniques to promulgate (Brosh 2003, 324), meaning that techniques did not remain tied to specific regions. Islamic glass is characterised by a mix of old and new decorative techniques – trailing, pinching, tonging, mould blowing, cutting, incising and engraving. Wheel-cut decoration was particularly popular with high quality colourless glass, while scratch (incised) decoration was often employed with dark cobalt-blue fabrics (Brosh 2003, 324). A fondness for superior quality, clear, colourless, glass is apparent at this time in the Islamic period with examples seen from Nishapur (Kröger 1995), Samarra (Lamm 1928), Ramla (Gorin-Rosen 2010A) and the Serçe Limanı shipwreck (Bass et al 2009), among other sites. Baker (2004) remarks that colourless glasses were favourably compared to rock crystal, with particular value given to clarity and transparency as aesthetically pleasing during the Early Islamic period.

4.1.3 Later Periods

In the late 12th to 14th century the actions of the Mongols in Iran and Iraq *'relegated to insignificance'* glassmaking in the Eastern Islamic Empire (Carboni 2001, 5), which did not recover until the 16th century. A different scenario developed in the eastern Mediterranean which Brosh describes as the *'golden age of Islamic art'* (Brosh 2003, 321), with new polychromatic techniques such as enamelling, gilding and marvering. Glassmaking thrived under the Ayyubid (1171-1260) and Mamluk (1250-1517) dynasties driven by royal patronage and increased demand for glass (ibid; Carboni 2001, 5). In the Levant, destruction of coastal cities during the Crusader period precipitated the decline of glass production at Tyre and Sidon in the 13th century. Damascus, Aleppo and Cairo were initially spared but the conquest by Tamerlane in 1401 also brought an end to production at these centres (Brosh 2003, 321).

Subsequent developments in artistic glass would concentrate in Europe as a result (ibid; Carboni 2001, 6).

4.2 Plant Ash Glass

The first glasses were made using ashes of halophytic plants from around the Late Bronze Age in Egypt and Mesopotamia. However, in around the 10th century BCE (Schlick-Nolte and Werthmann 2003), a transition occurred towards the use of mineral soda, natron, as the flux. This began in Egypt and expanded around the Mediterranean and Europe. The use of natron continued until approximately the 10th century CE, two centuries after the Islamic conquest. At this time plant ash once again began to be used west of the Euphrates, while in Europe, from around the 7th century, wood ash started to be utilized (Freestone et al 2008B). The dating of the transition from natron to plant ash in the eastern Mediterranean is most accurately reported from Egypt. Sayre and Smith (1974; although the data is first published in Sayre 1967) analysed 14 Egyptian coin weights inscribed with the names of Egyptian officials. The weights can be accurately dated to periods in which the officials were in office, and are recognised to cover the Umayyad to Mamluk dynasties. They ascertained that the latest natron glass weight dated to 833-842 CE and the earliest plant ash glass weight to 848-9 CE (Sayre and Smith 1974, 64). This implies that the flux transition took place during an approximate 6-16 year window, suggesting a flux change at around the mid-9th century. A second study by Gratuze and Barrandon (1990) analysed a further 70 Egyptian weights. Their latest natron glass sample dated to 868-893 CE, suggesting that natron production possibly continued for a further 20-60 years beyond that identified by Sayre and Smith (1974). A short period of overlap between the technologies is also recognised. The earliest plant ash glass analysed by Gratuze and Barrandon dated to 952-975 CE, however the large gap between samples is due to the limitations of the samples available and does not suggest a break in glass production. These are only two studies using specific object types and as such may not be representative of glass in more common circulation. Nonetheless, both studies

demonstrate that natron glass disappeared soon after the appearance of plant ash glass, implying a relatively fast transition. Analyses of plant ash glass from other sites in Egypt dating to the 9-10th century (e.g. Raya, Egypt) also support a mid-9th century flux change (Kato et al 2009; 2010A).

In Israel, the only suitable diachronic study covering the Early Islamic period was published by Fischer and McCray (1999) on glass from Sepphoris. They presented 65 vessel analyses covering a period from 37 BCE-1516 CE, of which 21 are dated to the Islamic period. Of the Early Islamic glass (640-1291) only 1 of 15 samples were plant ash and only 1 of 6 of the Later Islamic glass (1291-1516). They concluded that conservatism in the region's technological traditions may have inhibited the adoption of plant ash flux (ibid, 903-4) and that natron glass continued to dominate supply. Nevertheless, the limited number of samples and poor chronological resolution which was as a result of the "*sparse"* quantities of material culture in the Islamic period contexts as noted by Fischer and McCray (1999, 896) may have resulted in a dataset for the Islamic period that was not representative, potentially producing a misleading picture of the diachronic developments. At Caesarea, samples dating to the *"Early Islamic period"* present a more even mix of natron and plant ash samples, with the earliest well dated plant ash sample dating to 10-11th century and a less securely dated sample of glass waste potentially pushing this date into the 9-10th century (Brill 1999, 98-100). Therefore, a 9-10th century period for the appearance of plant ash glass in Palestine at this stage seems reasonable, with natron glass possibly continuing in production alongside.

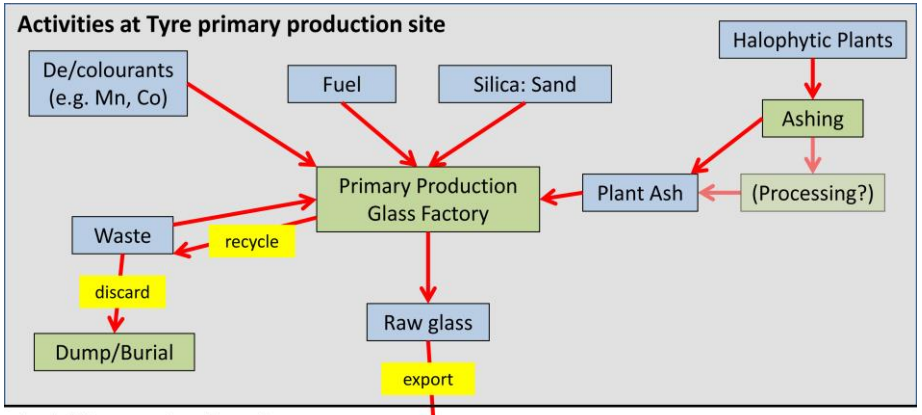
The earliest plant ash glass of the Islamic period is found in Raqqa, Syria (Henderson 1999; Henderson *et al* 2004), however, considering the uninterrupted use of plant ash glass in Mesopotamia, plant ash glass from earlier Islamic periods within Sasanian territories would be very likely. Nevertheless, compared to the Eastern Mediterranean region this is a relatively early appearance, which is likely due to Raqqa's close proximity to Sasanian glass making regions. In the 9th century plant ash glass already appears to be the dominant type in Raqqa, although natron glass continues to appear in some quantities until the 11th century, but possibly as relic or recycled fragments rather than new imports (Henderson et al 2004, 452).

As a final note, there is a small but growing body of evidence for the use of plant ash glass in Roman and Byzantine contexts, for example at Bubastis (Rosenow and Rehren 2014) and the Wadi Natrun (Picon et al 2008) in Egypt. It might suggest a possible plant ash glass tradition operating in the Eastern Mediterranean during the Roman-Byzantine period at a small-scale, maybe local, level.

Various reasons have been postulated for the abandonment of natron glass in favour of plant ash use. These range from climate change reducing natron production (Picon et al 2008; Foy and Nenna 2001; Saguí 2007), political instability in Egypt disrupting trade and extraction (Shortland et al 2006A; Whitehouse 2002) and cultural developments (Henderson 2013, 253-260). These possibilities are discussed in full in Section 9.3.

4.3 The Production of Islamic Plant Ash Glass

Plants high in alkali encompass several halophytic plant species (Turner 1956C; Barkoudah and Henderson 2006; Tite *et al* 2006; Brill 1970) common to semi-desert, coastal and salt marsh areas which are found to be fairly ubiquitous in the Levant (Ashtor 1992). Our understanding of plant ash glass production and supply in Early Islamic Palestine is confined to the finding of production sites at Tyre, Lebanon, and Raqqa, Syria, and a single workshop at Banias, Israel. Further evidence has come from a limited number of glass analyses from various consumption sites in Israel, e.g. Caesarea (Brill 1999), Sepphoris (Fischer and McCray 1999), and other sites across the caliphate, enabling some aspects of glass movement and production to be investigated. Certain regional studies of plant compositions have also helped our understanding of regional and interspecies compositional variations (e.g. Tite et al 2006). This section will discuss what is known of plant ash glass production through the use of the chaîne opératoire with reference to the primary production sites at Tyre and



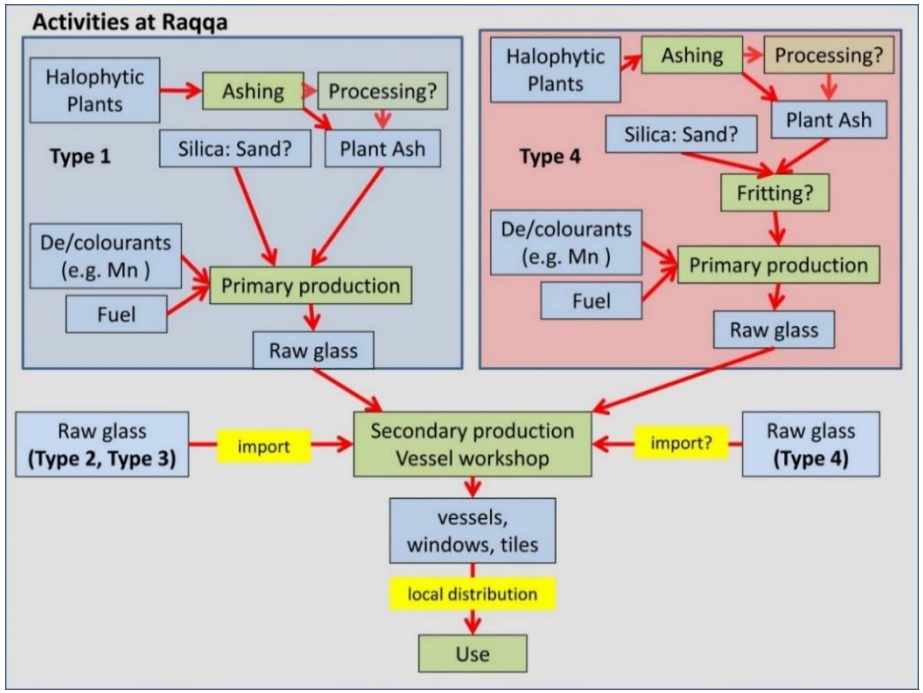


Figure 4.1 (left). Chaîne opératoire of Islamic plant ash glass production at Tyre and proposed activities operating at other locations. Only primary production is identified at Tyre as suggested from excavation and analysis.

Figure 4.2 (right). Chaîne opératoire of glass production at Raqqa. Both primary and secondary production were found to occur in close proximity. Raqqa Type 1 and 4 are suggested for primary production, of which the latter has evidence for a fritting phase. Raqqa Types 2, 3, and possibly also a variant of Type 4 is imported and altered though secondary working. Evidence suggests glass was used locally.

Figure 4.3. Map of Egypt, Syro-Palestine and the Middle-East (Mesopotamia and Iran) marking plant ash production and consumption sites acknowledged in the text.

Raqqa as presented in Figures 4.1 and 4.2. The locations of the sites mentioned in the test are displayed in Figure 4.3.

The chemical compositions of plant ash, the types of plants used, and the factors affecting plant ash compositions is discussed Section 5.5.

4.3.1 Primary Glass production at Tyre

Four tank furnaces were excavated at the island site of Tyre. Production and the furnaces are described in Jennings et al (2001) and Aldsworth et al (2002), analysis of the glass and details of the technology is provided in Freestone (2002) and documentary evidence for production is published in Carboni *et al* (2003). The four furnaces were all of a reverberatory design, consisting of a melting chamber and separate fire box at one end. They were constructed within the walls of existing, mainly Roman, buildings, and had internal surfaces lined with mortar. The furnaces were angled towards the centre of the island exposing the open fire box to the off-shore winds. The furnaces varied in size, as demonstrated in Figure 4.4. Furnace 1 was the largest with a melting chamber 6.4m by 3.9m and glass coating the walls up to 0.8m in height (Aldsworth *et al* 2002, 51), providing an estimated capacity of 37 tonnes (ibid, 66). This furnace shows evidence for 3 re-linings as seen from the mortar layers on the internal surface. A firing chamber stood at the east end, while an open area of compacted rubble floor was present at the opposite end. This is suggested as a possible loading platform for the raw materials (ibid, 53), which would most likely be loaded through the thin west end wall (see below). Furnace 2 was the most intact; with a near complete melting chamber floor and a twin firing chamber situated at floor level, it has an estimated 16 tonne capacity. As with furnace 1, a loading platform was positioned at the opposite end to the fire box. Examination of furnace 2 indicated that the wall nearest the loading platform was thinner. Aldsworth et al (2002) suggested that this wall could have been removed during furnace operation, to enable the charging of the raw materials on the loading platform (ibid, 62). It is also thought that the roof may have been permanent and the glass removed from beneath it (ibid 63), contra to the methods employed in the natron glass furnaces at Apollonia and Bet

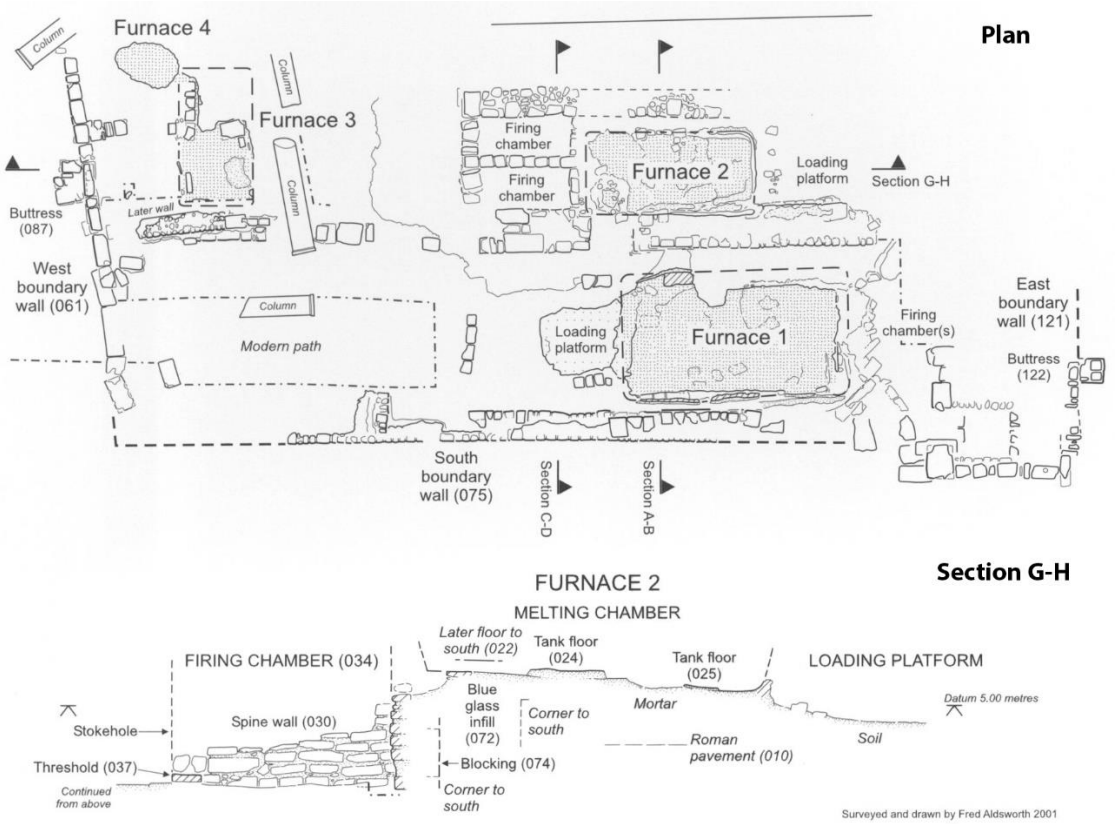


Figure 4.4. Plan and section of the furnaces from Tyre, four are marked. Image from Aldsworth et al (2002).

Eli'ezer (Gorin-Rosen 2000), although no superstructure survives in situ. Furnaces 3 and 4 were only partial remains. They showed signs for up to 5 reuses, and Furnace 3 has an estimated capacity of 13 tonnes (*ibid* 66).

Glass is a poor conductor of heat. Temperature modelling of a furnace the size of Bet Eli'ezer (8 tonne glass capacity) demonstrated that multiple charges of raw materials, ready mixed and added as layers, would be the most efficient method of heating the glass throughout (Van Beeumen et al 2011). Evidence for this is displayed in the layering observed in one of the raw glass chunks from Tyre (ibid, 64). No firm details on the duration of heating have been suggested, although duration could have been similar to that observed in the ethnographic study of Indian glass furnaces being in the vicinity of 30 days at 900°C (Sode and Kock 2001). Van Beeumen et al (2011) modelled a higher temperature of 1200°C through the burning of 70kg of wood per hour within a Bet Eli'ezer sized tank furnace, although a total reaction duration was not stated.

The operation of the glass making in Tyre is in many ways similar to the natron glass industry (cf. Figure 3.3). It was a single stage process with no evidence for fritting. Low-lime local sands were used *'from the same plain'* as Tyre, as described by William of Tyre writing in the 12th century (Carboni *et al* 2003, 146). The plant ash displays no evidence of processes such as ash washing which might demonstrate reduced lime and magnesia levels (McCray 1998). Only primary production is identified, with no secondary working, potentially demonstrating a continuation of the centralised production model. The scale of production is considerable – a single firing of furnace 1 alone would produce approximately a quarter of a million vessels at 150g per vessel (Aldsworth *et al* 2002, 66), clearly exceeding local use. Moreover, written evidence from the Cairo Geniza of the ordering of 37 bales of glass, calculated at around 8.4 tonnes, from Jewish producers in Tyre in 1011 provides addition evidence for the trade in glass from Tyre to Egypt, probably as raw chunks, (ibid, 65-6).

Manganese oxide was universally added to glass during the primary production stage (Freestone 2002, 72). Cobalt coloured glass was also found on site, suggesting that coloured variants were manufactured and that colourants might also have been introduced during primary production (Aldsworth et al 2002, 64). Freestone (2002, 68) also noted variable lime contents in the glass which resulted in higher amounts of high lime glass waste at the site. He suggested the cause was due to high variability of lime within the plant ash flux.

Pottery and glazed fragments suggested a 10th-11th century date for the site. This coincides with documentary evidence for glass production at Tyre between the 10-13th centuries (Carboni et al 2003). The earliest reference is by al-Muqaddasi, writing in 985 CE, who mentions the production of cut and mould blown glass (Aldsworth et al 2002, 65) and William of Tyre, writing before 1185, remarks on the *"remarkable and of outstanding clarity"* of the glass made at Tyre (ibid, 146).

As with the natron glass, understanding who controlled production is difficult to ascertain. Jewish families are mentioned in conjunction with a number of glass texts within the Cairo Geniza (Goitein 1961) and by Benjamin of Tudela, writing in 1167, who comments that the *"Jews [of Tyre] produce the fine glass called "glass of Tyre", which is prized in all countries"* (Carboni *et al* 2003, 145-6). Furthermore, ownership by

private enterprise, rather than official or state organisation, is implied by the translated phrase '*Jewish firms'* used in relation to procurement of glass from Tyre (Goitein 1967, 421). Therefore, a possible Jewish connection with production and management by Jewish families or businesses, is the most evidenced.

4.3.2 Glass Production at Al-Raqqa

Al-Raqqa, located in modern day Syria, is situated on the banks of the Euphrates near the Sasanian-Byzantine border. Founded as a Hellenistic city named Kallinikos, it was conquered in 640 CE. A garrison was built under al-Mansur in 771-2 and from 796-808 the city became the residence of Caliph Harun al-Rashid (Henderson 1999, 226; Heidemann 2006). It was during the period of Harun al-Rashid's residence that it became the de facto capital and underwent expansion, including the building of several palaces, and a large extramural industrial complex situated between al-Raqqa and the newly founded city of al-Rafika (Heidemann 2006). The city boasted port facilities and was situated along the main postal road between Baghdad and Damascus. The extensive industrial remains found at Raqqa include glazed pottery production and glass working debris. The glass working remains have been published in a large number of reports (Henderson 1995; 1999; 2002; 2003A; 2013; Henderson et al 2004; 2005A; Khalil and Henderson 2011). This work has revealed a complex picture of primary and secondary production utilising four principal compositional groups, spread over four localities and several centuries. The most extensive remains date from the late 8th–early 9th century and arise from two sites: Tel Zujaj, discussed in some detail by Henderson (1995; 1999), and with further evaluation and more analysed samples in Henderson et al (2004) and Tel Abu Ali, which is subject to only a brief excavation report by Khalil and Henderson (2011). Later remains come from 11th century at Tel Fukhkhar (Henderson et al 2004) and 12th century Tel Bellor (not fully published).

4.3.2.1 Tel Zujaj and Tel Abu Ali

Excavations at Tel Zujaj suggest three phases of activity. The total chronology is suggested to span just a 30-year period coinciding with the residence of Harun al-

Rashid in Raqqa (Henderson 1999, 230), however, a sherd of Samarran lustre-ware found in late phase contexts was in use until the late Abbasid period indicating a late date for the site is viable (ibid, 229). The mid-phase, which contains the contexts with the glass workshop, has a *terminus ante quem* of 804 CE based on a coin within a fill dumped into the workshop after it ceased operation. Henderson suggests that the workshop was in use prior to this date (ibid, 229). The ceramics from contexts contemporary with the workshop are Abbasid.

Evidence for primary production was uncovered in the last phase of the site. The primary production debris consisted of 4-5 tonnes of dumped vitrified furnace bricks and furnace floor fragments up to 1m in length, coated with glass and interpreted as tank furnace remains (Henderson 1999, 226; Henderson *et al* 2004, 446). In addition, a robbed pit containing charcoal fragments, burnt bone and glass waste was interpreted as a below ground firing chamber, although no *in situ* furnace remains were found. There were also quantities of partially vitrified grey material, interpreted as frit, as well as the foundations of two small vitrified structures, understood as possibly fritting ovens. This late phase also contained some secondary production waste including glass moils, dribbles, raw glass, crucible and casting tray fragments. It is most likely that secondary working was occurring in this phase as well as earlier phases (Henderson 1999, 230). The debris described here overlays and post-dates that of the glass workshop in the mid-phase discussed below.

The middle phase contained evidence for secondary production and implies a glass workshop (Henderson 1999, 226) with three, possibly four, partially destroyed furnaces. Furnace 1 is interpreted as a 3 chambered furnace, of which only the lowest chamber and floor of middle chamber survive (ibid, 226). It was termed a *'bee-hive'* or *'southern furnace'* (ibid, 228; Henderson et al 2004, 441; see Figure 4.5). A fire is suggested to have been placed in the bottom-most chamber and glass was melted in a crucible in the central chamber. A nearby semi-circular structure was postulated as an annealing hearth. Furnaces 2 and 3 were similar in shape, while very little remained of furnace 4. All 4 furnaces are reported to have an approximate diameter of 75cm (Henderson 1999, 248), although Figure 4.5 suggests a much smaller internal diameter than this. Each furnace was connected to an under floor flue system. Other debris from

the workshop includes moils, rods, dribbles, drops, raw glass lumps and glass of various colours (Henderson 1999, 230). Crucible fragments, while reported, and suggested that they were used in the workshop, are not described (Henderson *et al* 2004, 441). In addition, stone blocks, that have been interpreted as casting trays for the manufacture of tesserae and flooring tiles, are also described, although the evidence for this usage is not entirely convincing.

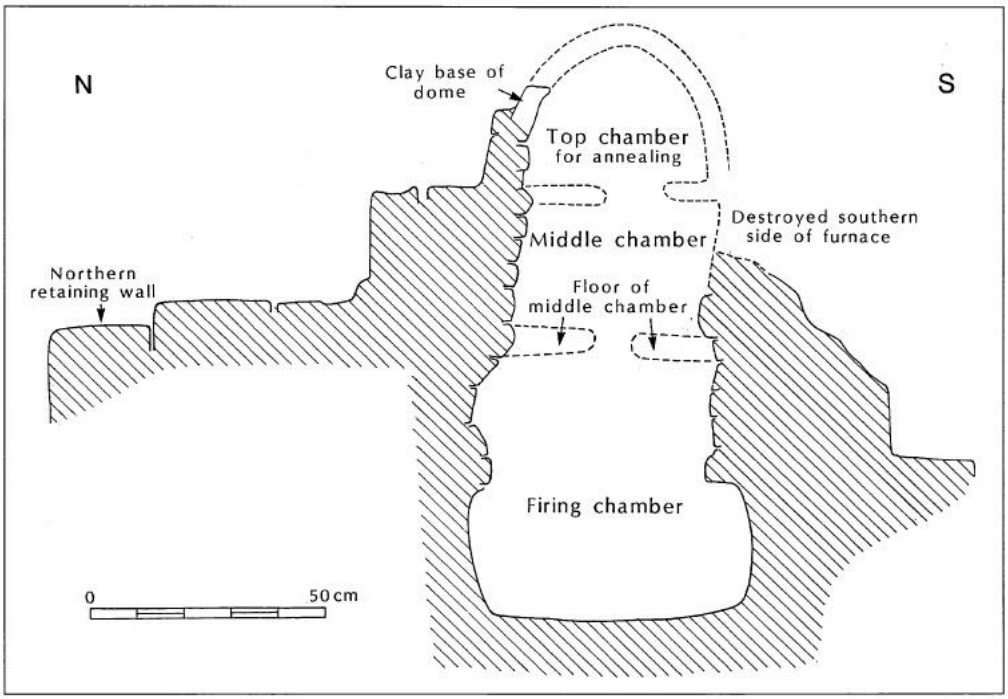


Figure 4.5. Schematic through furnace 2, one of the 'bee-hive' furnaces from the glass workshop in Raqqa taken from Henderson (1999, 228).

The earliest phase held a hypocaust system (Henderson 1999, 229) of which a Byzantine or early Umayyad date is suggested (Henderson 1995, 63).

The only *in situ* tank furnace remains come from the nearby contemporary area of Tel Abu Ali, also situated within the Raqqa industrial zone (Khalil and Henderson 2011). It was discovered during later excavations at Raqqa. The evidence for glass production consists of a rectangular tank furnace and possibly another circular furnace. The former consists of a melting chamber floor with adhering greenish and purplish glass measuring 3.7m by 2m. The chamber wall survives to 0.4m, with a *'slagged inner surface'* visible up to 0.28m (ibid, 238). Although adhering glass was not found on the inside wall, the slagged inner surface suggests a potential theoretical minimum height

of glass from which a volume of glass can be calculated at just over $2m^3$. This implies an estimated minimum capacity of around 5 tonnes using an average glass density of $2.5g/cm^3$. The furnace was faced with slabs of stone, rather than a mortar lining as seen at Tyre. The floor had two courses, indicating at least 2 reuses. It is noted that the flooring material is similar to the production waste found at nearby Tel Zujaj and Tel Bellor, demonstrating these sites' association to primary production activities (Khalil and Henderson 2011, 239). The firing chamber was positioned below floor level, directly under the melting chamber, this allowed the air to be drawn up into the furnace over the glass (ibid, 240) using the chimney effect and not wind-blown as in the furnaces of Tyre, Apollonia and Bet Eli'ezer. The firing chamber itself contained fine charcoal fragments and numerous olive pits, suggesting the use of waste from the olive oil industry. As at Bet Eli'ezer and Apollonia, the furnace was assumed to been barrel vaulted, which was then removed to facilitate glass collection. A potential second furnace, semi-circular in structure with a floor of stone slabs and adhering purple and green glass was also noted and interpreted as primary production. No dimensions are supplied. The reported dating of this site from the associated Abbasid pottery is no later than the 9th century and is probably contemporary with production seen at Tel Zujaj (ibid, 242).

4.3.2.2 Tel Fukhkhar and Tel Bellor

Tel Fukhkhar is dated to the 11th century. The analytical work is described in Henderson *et al* (2004), however the archaeological glass working remains are not discussed in any detail and simply recounted as *'raw green glass attached to dumped tank furnace fragments and deposits of raw glass'* (*ibid*, 42). Unlike Tel Zujaj, no furnace floors were found, nonetheless hundreds of vessel fragments were. Therefore, while primary production is suggested, the evidence as presented is only conclusive for secondary working thus far.

Tel Bellor, dating to the 12th century, was another glass working site within the Raqqa industrial zone. It is reported to contain tank furnace remains as well as a fritting oven, although no further information has been provided and no analysis has been performed (Henderson *et al* 2004, 442).

4.3.2.3 The Compositional Evidence

The archaeological evidence suggests a mix of primary and secondary production at Raqqa with primary and secondary production remains from the middle and late phases at the late 8th/early 9th century Tel Zujaj and possibly at 11th century Tel Fukhkhar. Primary production is also attested to 12th century Tel Bellor, although lacking published evidence, and an *in situ* tank furnace, suggesting primary production, is described from late the 8th/early 9th century Tel Abu Ali.

Analysis of raw glass, vessel fragments and working waste has indicated a complicated picture involving four compositional groups (Types 1, 2, 3 and 4) at Tel Zujaj (Henderson 1995; 1999; Henderson *et al* 2004) and the same plus a further sub-group (Type 1a) at Tel Fukhkhar (Henderson *et al* 2004), although by this time Types 2, 3 and 4 are in small enough quantities to be residual or recycled only. There are no published analyses from the other two sites (Tel Abu Ali, Tel Bellor). In addition, analyses were conducted of vessels and window glass from nearby palace complexes (Abbasid Western and Eastern Palaces and the later Ayyubid Princesses Palace) with the aim of matching production debris with finished objects (Henderson 1999, 231).

At Tel Zujaj Raqqa Type 1, a plant ash glass with low alumina content, predominated. Object analyses found it used in cast glass tiles and vessels but not identified in Abbasid window glass, as seen from the palace complexes (Henderson 1999, 233). Type 3 on the other hand was an imported natron glass of a Levantine type (Henderson et al 2005B) utilised in window and vessel glass. Type 2 was found only in later phases at Tel Zujaj (the dumped material). This type was suggested as a mix of Types 1 and 3 by Henderson (1999, 234), but this was ruled out in later articles due to the low levels of lime and different alumina, suggesting a different silica and plant ash source (Henderson et al 2004, 460). This glass type has a higher frequency of coloured examples, and has been found to have been used for cast and vessel glass but not windows. Finally, Type 4 was a glass with a wide compositional spread, especially in alumina and flux elements, but with generally high alumina and magnesia content, and therefore represents another different plant ash source. This type was described as an *"experimental type"* by Henderson *et al* (2004, 456), and was suggested as possible mix

of two glass compositions. This glass was used for windows and vessels, and is the only one to be found at both the western and eastern palace complexes (Henderson 1999, 233). Raqqa Type 4 also matched the grey semi-vitrified material interpreted as frit, and is therefore the only compositional type to be linked to a frit-like material (ibid), although only a single frit fragment was analysed so this finding may not be representative.

What glass types were being primary produced at Raqqa? At Tel Zujaj Raqqa Types 1, 2 and 4 were found adhering to the inside of material interpreted as being tank furnaces fragments (Henderson 2004, 451). If tank furnaces were only used for primary production, then it suggests that at least three different glass types were being manufactured from their raw materials at Raqqa. However, tank furnaces can also be used to re-melt glass as part of secondary working (Wardle and Shepherd 2015). Therefore, Type 1, being the most abundant at Tel Zujaj and Tel Fukhkhar, is probably the most likely candidate for a primary produced local glass, while Type 2, present in much smaller quantities, could be imported. Type 4, another abundant type, is more complicated. This group is possibly a mix of two glass types, both of which are here noted to be similar to Sasanian compositions (discussed below). Furthermore, only the high MgO, low Al_2O_3 end-member is associated with material interpreted as frit (Henderson et al 2004. 451-2). If this interpretation is correct, it suggests that a two-stage glass making process was in operation for this type. The frit is described as *'semi-vitrified greyish'* material and contained unreacted particles of alkali feldspar and quartz (Henderson 1999, 235) and also calcium phosphate fragments interpreted as bone fragments (ibid). The frit could also be un-reacted batch (ibid). With regards to the use of a fritting process for other glass types, Brill (2005, 71) similarly reported the remains of semi-vitrified frit-like material in glass waste dumps of Sasanian contexts, although no analysis and no further investigations were carried out. It suggests that at least one end-member of Type 4 was being produced at Raqqa, while the other might have been produced at Raqqa but could also have been imported from Mesopotamian regions. The waste material also potentially suggests that this glass type, and possibly Sasanian glass in general, employed a two-stage process. If true, this implies that the

Raqqa Type 1 and Type 4 followed separate chaîne opératoires, despite both being produced at Raqqa, and this implies differing technological origins.

It is noted that all four glass types are presented by moils at Tel Zujaj (dating 8th-9th century), implying that all 4 types were worked into objects at Raqqa.

The situation at 11th century Tel Fukhkhar is similar: 75% of the analysed materials were Type 1, with only small quantities of Type 2, 3 (1 chunk and 3 vessel fragments) and 4. These latter three types possibly exist as relict or recycled fragments only at this time (Henderson *et al* 2004, 452). Primary production is most likely only to include Type 1.

Manganese oxide is universally added to Type 1 and Type 2, and to approximately half of the Type 4 glass, with no correlation with either end member. Manganese oxide was not added to Type 3, the natron glass.

The organisation of production at Raqqa is distinctly different from that seen at Apollonia, Bet Eli'ezer and Tyre. Raqqa contains primary and secondary production operating at the same time during the late 8th/early 9th and the 11th centuries. Production at Tel Abu Ali and Tel Zujaj were operating during a period of palace construction and expansion of the city and so far appears that primary production (Types 1 and 4) was for local use at Raqqa and not exported to other sites, although Raqqa Type 1 is reported at Raya (Kato et al 2010A), high quality contemporary comparative data is lacking. At current, a centralised production model, in a framework identified for natron glass, does not appear to be in operation at Raqqa. Nonetheless, the use of the glass in state construction potentially suggests state organisation on a localised scale for glass making operations at Raqqa, at least during the late 8th/early 9th century period and potentially later. State organisation and the need for large quantities of glass in a relatively short time period for construction projects could be the reason why so many diverse compositional groups are present in one location. There is also the possibility that it might represent the convergence of two different glassmaking traditions, an Eastern Mediterranean Islamic plant ash technology and a Sasanian technology, implying workers from two different traditions. This is further discussed in Section 9.4.

4.4 Defining Regional Plant Ash Glass Groups

Byzantine period natron glass is distinguished by a centralised glass industry consisting of relatively few compositional groups representing different production locations. Plant ash glass of Sasanian and Early Islamic period can be broadly separated into two regional groups – Mesopotamian and Eastern Mediterranean – based around MgO and K_2O as demonstrated in Freestone (2006, 204). Other studies have identified smaller regional compositional groups, for example Coloured and Colourless groups from Nishapur (Brill 1995; Wypyski 2015), three Sasanian groups from Veh Ardašīr (Mirti *et al* 2008; 2009) and Group 3 (Gratuze and Barrandon 1990) from Egypt, as well as Raqqa Types 1, 2 and 4 (Henderson 1999; Henderson *et al* 2004) and Tyre glass (Freestone 2002) already noted. More recently Henderson et al (2016) has suggested a dispersed model of production for the region of Syria, with cities having their own glass regional sub-groups. The understanding of plant ash glass groups lags behind that of natron glass, nonetheless, broad regional compositional groups of plant ash glass are starting to emerge, and these are now being utilized in provenance studies (e.g. Kato *et al* 2010A; Gratuze and Foy 2012; Brill and Stapleton 2012). This section will provide a critical reassessment of current plant ash glass data in order to identity and characterise the main regional compositional groups. Selected analyses of glass from three regions of the Islamic caliphate will be investigated to identify manufacturing trends, raw materials and compositions. Glass will be chosen from Syro-Palestine, Mesopotamia and Egypt. These regions are selected because of their close proximity to Palestine and known or historic glass industries. Glass from Turkey and Europe will not be part of this study as the Near East traditionally did not import glass from these regions.

4.4.1 Glass from Syro-Palestine

The regions of Syria and Palestine contain the only identified Islamic plant ash glass production sites, found at Tyre and Raqqa, and these will be used to create the compositional signature for this region. Palestine itself has no primary production,

however a single secondary workshop site at Banias (Freestone *et al* 2000) will also be included as a comparator. There are, in addition, a number of analyses from local consumption sites: 7th-12th century vessels from Al-Hadir (Gratuze and Foy 2012); 8th-12th century vessels, waste and chunks from Caesarea (Brill 1999B; Brill and Stapleton 2012); and several tonnes of raw and cullet glass from the Fatimid period (1025 CE) Serçe Limanı shipwreck found off the coast of Turkey (Bass *et al* 2009; Brill 2009). An additional body of data from various sites has been published by Henderson et al (2016), of which 6 samples come from 8th century Khirbat al-Minya, Israel, 7 samples from 12th-14th century Beirut, Lebanon, and 8 samples from 12-14th century Damascus, Syria. However, visual assessment of the data from these sites suggests that each assemblage consisted of glass of more than one production type, and due to the potentially mixed provenance these sites cannot be used to define regional production, although they will serve as comparative material in Section 9.5. Therefore, only material from the production sites at Raqqa, Tyre and Banias will be used to define regional production types. Averages for these sites are presented in Table 4.1.

4.4.1.1 The Tyre Glass

The Tyre glass is defined by unpublished LA-ICP-MS analyses (Phelps and Freestone) of the samples described in Freestone (2002), the full data is presented in Appendix B. These samples consist of raw chunks and furnace glass. High lime in some samples led to them being thought of as discarded waste and not representative of the end product (ibid), therefore one sample with 17% lime has been removed from the average. A further sample of cobalt blue glass was also removed. The glass at Tyre is characterised by flux elements with mid-levels of MgO (3-4%) and K_2O (av. 2.3%), and particularly high lime (av. 11.2%; range 8.5-14.1%). MgO/CaO and K_2O/P_2O_5 ratios, representing the type of plant ash flux used, are low at 0.32 and 6.75 (Table 4.2). Of the sand fraction, alumina is quite low (av. 1.8%), as are heavy mineral elements (av. 0.5% Fe_2O_3, 0.09% TiO_2 and 52ppm ZrO_2), whose abundance is similar to the Levantine natron glasses suggesting a similar geological origin of the coastal sands sourced although the alumina content is lower. Note that the lime source is mainly from the plant ash, as demonstrated by Freestone (2002, 72).

Table 4.1. Mean values (m) and standard deviations (sd) for plant ash glass groups. Data from literature and new LA-ICP-MS analyses, see base of table. Values as weight % except ZrO_2 as ppm. Mesopotamian glass continued on next page.

Location	Reference	Type	Date	Method	N		Na_2O	MgO	Al_2O_3	SiO2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	ZrO_2
Syro-Palestine																		
Tyre, Lebanon[1]	Freestone 2002*	**Tyre Type**	10th-11th	LA-ICP-MS	8	**m**	**12.85**	**3.61**	**1.81**	**65.06**	**0.33**	**0.76**	**2.26**	**11.21**	**0.09**	**1.33**	**0.54**	**52**
						sd	*1.22*	*0.26*	*0.32*	*1.65*	*0.05*	*0.11*	*0.22*	*2.15*	*0.01*	*0.67*	*0.05*	*3*
Banias	Freestone 2000*		11th-13th	LA-ICP-MS	12	**m**	**11.98**	**2.40**	**1.21**	**71.65**	**0.24**	**0.86**	**1.52**	**8.59**	**0.12**	**0.83**	**0.48**	**170**
						sd	*0.57*	*0.57*	*0.62*	*1.15*	*0.04*	*0.07*	*0.35*	*0.98*	*0.02*	*0.28*	*0.10*	*38*
Raqqa, Syria	Henderson et al 2004	**Raqqa Type 1**	8th-11th	EPMA	90	**m**	**12.93**	**3.43**	**1.20**	**67.49**	**0.28**	**0.77**	**2.52**	**9.31**	**0.07**	**1.14**	**0.56**	**142‡**
						sd	*1.40*	*0.32*	*0.19*	*1.51*	*0.04*	*0.13*	*0.36*	*1.45*	*0.01*	*0.55*	*0.31*	*13*
		Raqqa Type 4	8th-11th	EPMA	73	**m**	**14.37**	**5.12**	**2.43**	**65.78**	**0.29**	**0.59**	**2.85**	**6.25**	**0.11**	**0.82**	**0.95**	**132‡**
						sd	*1.60*	*1.08*	*1.15*	*3.00*	*0.38*	*0.15*	*0.64*	*1.37*	*0.04*	*0.79*	*0.54*	*50*
Egypt																		
Fustat[2]	Gratuze and Barrandon 1990	**Egypt Group 3 (A)**	10th-11th	NAA	7	**m**	**14.00**	**2.83**	**2.24**	**66.17**	**n/a**	**n/a**	**2.26**	**9.17**	**0.17**	**1.20**	**0.85**	**96**
						sd	*1.24*	*0.28*	*0.11*	*1.19*	*n/a*	*n/a*	*0.28*	*0.36*	*0.02*	*0.08*	*0.13*	*20*
		Egypt Group 3 (B) - Tyre Type?	10th-11th	NAA	6	**m**	**14.08**	**2.87**	**1.78**	**66.73**	**n/a**	**n/a**	**2.68**	**8.97**	**0.10**	**1.32**	**0.48**	**56**
						sd	*2.03*	*0.27*	*0.13*	*1.92*	*n/a*	*n/a*	*0.46*	*0.80*	*0.01*	*0.33*	*0.06*	*3*

Table 4.1 continued

Location	Reference	Type	Date	Method	N		Na_2O	MgO	Al_2O_3	SiO2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	ZrO_2
Mesopotamia-Iran																		
Veh Ardasir, Iraq	Mirti et al 2008; 2009	**Sasanian 1a**	3rd-7th	sol ICP-MS	29	**m**	**16.01**	**4.05**	**2.28**	**60.02**	**0.31**	**n/a**	**3.32**	**6.70**	**0.18**	**0.15**	**1.09**	**305**
						sd	*1.39*	*0.43*	*0.57*	*2.52*	*0.06*	*n/a*	*0.42*	*1.03*	*0.04*	*0.42*	*0.32*	*118*
		Sasanian 1b	3rd-7th	sol ICP-MS	11	**m**	**16.02**	**4.10**	**2.19**	**60.49**	**0.27**	**n/a**	**3.41**	**6.74**	**0.13**	**0.12**	**0.91**	**64**
						sd	*1.44*	*0.43*	*0.34*	*1.76*	*0.07*	*n/a*	*0.40*	*0.83*	*0.03*	*0.25*	*0.21*	*20*
		Sasanian 2	3rd-7th	sol ICP-MS	13	**m**	**17.43**	**7.13**	**1.62**	**58.63**	**0.13**	**n/a**	**2.80**	**5.55**	**0.09**	**0.18**	**0.60**	**71**
						sd	*1.14*	*0.93*	*0.41*	*3.16*	*0.02*	*n/a*	*0.42*	*0.88*	*0.02*	*0.21*	*0.17*	*18*
Nishapur, Iran	Brill 1995†	**Nishapur Colourless Type**	9th-10th	LA-ICP-MS	22	**m**	**12.53**	**4.69**	**1.17**	**71.18**	**0.12**	**0.65**	**2.45**	**6.27**	**0.05**	**0.40**	**0.37**	**73**
						sd	*1.48*	*0.57*	*0.48*	*2.52*	*0.06*	*0.08*	*0.38*	*0.67*	*0.03*	*0.20*	*0.23*	*39*
		Nishapur Coloured Type[3]	9th-10th	LA-ICP-MS	15	**m**	**15.86**	**3.76**	**3.05**	**64.68**	**0.32**	**0.76**	**2.91**	**6.78**	**0.15**	**0.39**	**1.12**	**130**
						sd	*1.63*	*1.22*	*0.83*	*2.63*	*0.08*	*0.19*	*0.50*	*1.03*	*0.04*	*0.45*	*0.20*	*42*
Samarra[4]	Wypyski 2015	**Type A**	9th-10th	SEM-WDS	44	**m**	**13.93**	**5.35**	**1.07**	**68.95**	**0.11**	**0.79**	**2.79**	**5.71**	**0.05**	**0.60**	**0.31**	**n/a**
						sd	*1.42*	*0.41*	*0.23*	*2.06*	*0.02*	*0.10*	*0.42*	*0.90*	*0.02*	*0.60*	*0.11*	*n/a*
		Type B	9th-10th	SEM-WDS	12	**m**	**14.73**	**3.23**	**2.45**	**65.50**	**0.29**	**0.78**	**3.10**	**6.40**	**0.15**	**1.99**	**1.03**	**n/a**
						sd	*1.86*	*0.27*	*1.16*	*3.52*	*0.05*	*0.19*	*0.29*	*1.26*	*0.06*	*1.21*	*0.50*	*n/a*
Samarra	Henderson et al 2016		9th-10th	LA-ICP-MS	21	**m**	**15.11**	**7.17**	**1.22**	**64.66**	**0.07**	**n/a**	**2.38**	**5.33**	**0.09**	**2.35**	**0.50**	**185**
						sd	*14.52*	*6.66*	*0.94*	*67.92*	*0.08*	*n/a*	*2.45*	*5.09*	*0.06*	*0.85*	*0.40*	*96*

* samples re-analysed by Phelps and Freestone (data Appendix B)

† = samples re-analysed by Lankton (pers. comms.)

‡ = data Henderson et al 2016

1 = cobalt coloured and single very high lime sample omitted

2 = outliers and Mamluk dated samples omitted. Data split into two groups by Ti/Zr ratio detailed in text.

3 = self-coloured samples only, deliberately coloured samples omitted

4 = deliberately coloured samples omitted

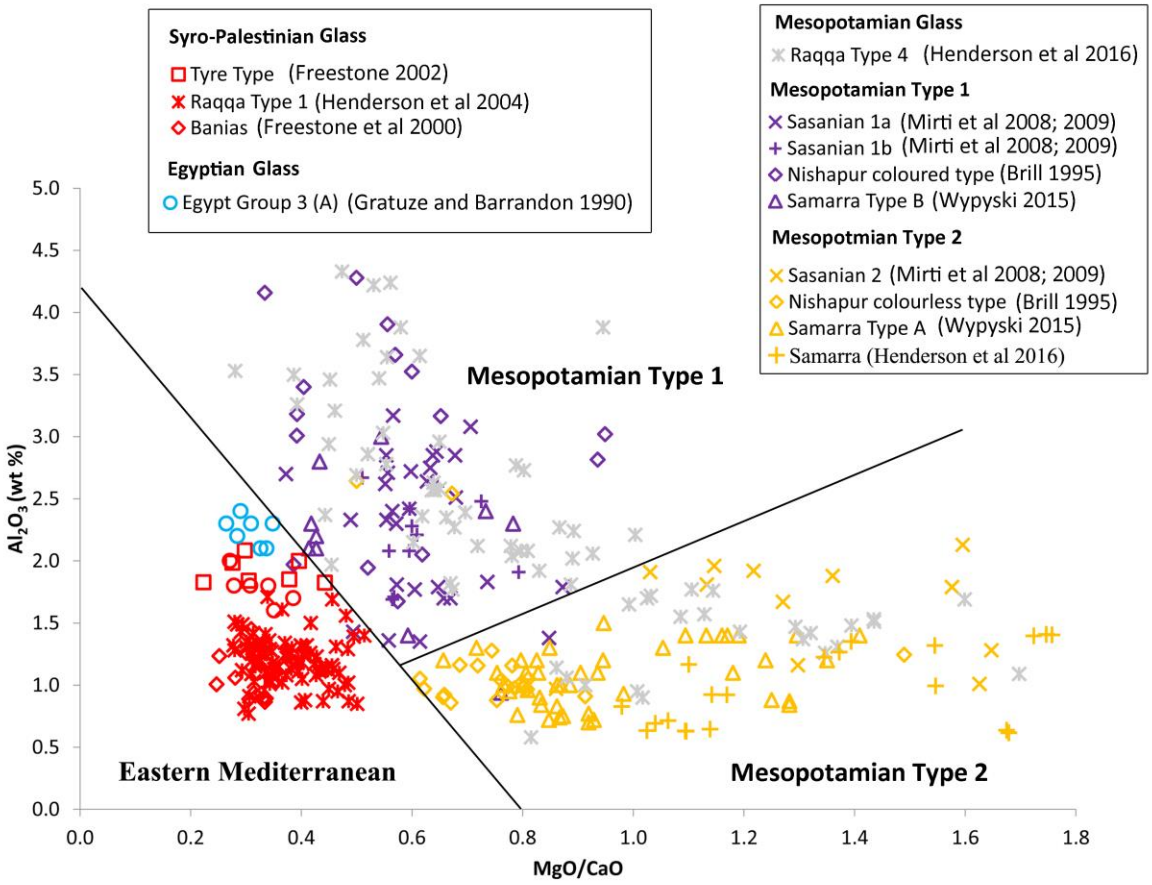


Figure 4.6. Data from Egypt, Syro-Palestine, Mesopotamia and Iran demonstrating that glass can be divided into three main compositional groupings based mainly upon flux content. These groups are designated Eastern Mediterranean; Mesopotamian Type 1; and Mesopotamian Type 2. This suggests that three principal flux types were in use during the Sasanian and Islamic periods.

4.4.1.2 The Raqqa Glass

Two plant ash types are suggested here as potentially primary produced at Raqqa: Type 1 and 4. The data is provided from Henderson et al (2004). Type 1, the dominant type, is quite close to the Tyre composition: similar mid-levels of MgO (3-4%), K_2O (av. 2.5%), high CaO (av. 9.3%), and corresponding, but slightly higher, MgO/CaO and K_2O/P_2O_5 ratios at 0.37 and 8.84 (Table 4.2). The close correlation between Tyre and Raqqa Type 1 is illustrated in Figure 4.6. For Raqqa Type 1 it appears that a degree of care was taken in choosing a pure sand with low levels of alumina (av. 1.2%), low titania (0.07%) and iron oxide (0.56%). These values are lower than Tyre.

Table 4.2. Selected element ratios from the flux and accessory minerals of the glass groups presented in Table 4.1. Glass groups are separated as demonstrated in Figure 4.6.

Site and Type	MgO/CaO	K_2O/P_2O_5	Al_2O_3/TiO_2
Eastern Mediterranean			
Tyre	0.23	6.75	19.29
Banias	0.28	6.45	10.06
Raqqa Type 1	0.37	8.84	18.15
Egypt Group 3A	0.31	n/a	12.98
Egypt Group 3B	0.32	n/a	17.26
Mesopotamian 1 Type			
Sasanian 1A	0.6	10.59	12.70
Sasanian 1B	0.61	12.45	17.38
Nishapur Coloured	0.55	9.13	19.70
Samarra Type B	0.5	10.45	16.18
Mesopotamian 2 Type			
Sasanian 2	1.29	21.1	18.83
Nishapur Colourless	0.75	19.73	22.15
Samarra Type A	0.94	25.74	21.83
Samarra (Henderson et al 2016)	1.31	31.89	13.77
Mixed Mesopotamian			
Raqqa Type 4	0.82	9.72	21.99

Raqqa Type 4 is very different from Type 1. The magnesia (5.1%) and alumina (2.4%) averages of this group masks a considerable compositional range – 2-8% MgO and 1-4% Al_2O_3. Lime is variable but relatively low (av. 6.25%). The MgO/CaO and K_2O/P_2O_5 ratios are considerably higher than glass from Tyre and Raqqa Type 1 at 0.82 and 9.72. This is a closer match to Mesopotamian glass types (Table 4.2). The broad range of MgO and Al_2O_3 has led Henderson et al (2004, 58-60) to suggest that Raqqa 4 is a combination of two glass types: one of high MgO and low Al_2O_3 and one of low MgO and high Al_2O_3. These glasses would be made of different plant ash and silica components. Compositions between these end-members would fall on a mixing line. Henderson suggests that Raqqa Type 4 was potentially an experimental type, however, comparisons to other Mesopotamian glass of Sasanian and also Islamic origins has indicated close similarities, especially to Sasanian groups. It is possible that this glass type could be made using Sasanian traditions and that Sasanian glassworkers could

have been brought to Raqqa. This might also explain why a fritting stage is associated with this type but not Raqqa Type 1.

4.4.1.3 The Banias Glass

The inland site of Banias, Israel, is a secondary workshop site (Freestone et al 2000) most recently dated to the 11-13th century (Freestone pers. comms.). The glass, re-analysed by LA-ICP-MS (Phelps and Freestone, see Appendix B), is relatively low in MgO (av. 2.4%) and Al_2O_3 (av. 1.2%), high lime (av. 8.6%), and has flux element ratios of 0.28 MgO/CaO and 6.45 K_2O/P_2O_5. These values are fully consistent with other Syro-Palestine glasses. This glass is most similar to Raqqa Type 1 (Figure 4.6), although with elevated titania.

4.4.1.4 Summary

In summary, Syro-Palestine glasses (not including Raqqa 4) are characterised with 2-4% MgO, 8-12% CaO, and MgO/CaO and K_2O/P_2O_5 flux ratios of 0.3-0.4 and 6-9. All these glasses exhibited additions of MnO (av. 0.83-1.3%). They demonstrate a close correlation of flux type, suggesting the use of similar plant species from similar geological situations.

4.4.2 Glass from Egypt

Well contextualised, high quality analyses are rare for early Islamic Egypt. Analysis is mainly confined to a limited number of consumption sites; 9-13th century Fustat (Brill 1999; Sawada et al 2005; Kato et al 2010B); 9-10th century Siraf (Brill 1999) and 9-12th century Raya (Kato et al 2010A). Unfortunately, due to a combination of poor chronological context, glass of mixed provenance and a lack of both accuracy and precision in some analytical techniques, none of these sites are suitable for defining regional compositional groups. Therefore, at this stage Egyptian production will be characterised only by glass weight standards analysed by Gratuze and Barrandon (1990). These samples are chosen due to the high quality of analytical technique

(NAA), secure dating and increased likelihood of being of Egyptian origin. Nonetheless, the samples of Group 3 cluster into two groups, one of which (here designated Group 3A) has higher titania, iron, zirconia and alumina and the other (Group 3B) which closely matches the composition of glass from Tyre and is consequently, potentially imported. Table 4.1 presents the averages of these two groups, note that only the Abbasid-Fatimid dated samples are used, with the Mamluk samples omitted in order to match the date period of the thesis.

Group 3A is characterised by accessory minerals in the sand, with high levels of alumina (av. 2.2%), titania (av. 0.17%), and relatively high iron oxide (av. 0.85%) and 96ppm zirconia. While these values are lower than those observed in the Egyptian natron glasses (Egypt I and II), these heightened values of heavy mineral elements have been identified as typical of Egyptian sands and glass (Foy et al 2003A; Nenna 2014), and therefore this glass probably represents Egyptian production. The flux elements, on the other hand, show similarity with Syro-Palestine production. They share a low MgO (av. 2.8%) and K_2O (av. 2.3%) content and both have high lime (av. 9.2%). The MgO/CaO ratio at 0.32 is also very similar to general Syro-Palestine levels (P_2O_5 data was not available).

While the sand is distinct, the flux shows an adherence to the same traditions as those from Syro-Palestine. Potential reasons for this are that related plant species grew in both regions, that the geology enabled equivalent soil chemistry, or conceivably that there was a unity of techniques – they chose the same plants, ashed and processed them in the same way. It is probably a combination of all these factors, but it does, at the very least, suggest a commonality between the plant ash glass technologies of Egypt and Syro-Palestine which is not shared by Mesopotamian plant ash glass, and therefore can be described as an Eastern Mediterranean glass making tradition.

4.4.3 Glass in Mesopotamia and Iran

Studies of glass in Mesopotamia and Iran have identified several well dated compositional groups, although no production sites have been investigated despite a number of potential Sasanian (Simpson 2014; Kröger 1995) and Islamic glass

production sites being identified (Samarra; Northedge and Falkner 1987). While the region around the Mediterranean switched to natron flux in the 1st Millennium BCE, there was no such break east of the Euphrates river. Studies of excavated Sasanian glass (Whitehouse 2005; Simpson 2014; Negro-Ponzi 2002; 2005) have led to a number of analyses (Brill 1999; 2005; Mirti *et al* 2008; 2009) and the identification of a few compositional groups.

4.4.3.1 Sasanian Production: Veh Ardašīr

Sasanian glass data is represented by the work of Mirti *et al* (2008; 2009). The glass from this study has certain advantages; most samples come from a single location, the vessels are well contextualised and the analysis was performed by solution ICP-MS, a high precision technique with low detection limits. The glass came from excavations at Seleucia and Veh Ardašīr and date to the Parthian (1st-3rd) and Sasanian (3-7th century) periods. Three groups were identified by Mirti et al (2009) and are presented in Table 4.1 with outliers, intermediate and coloured samples having been removed (see Mirti *et al* 2009, 1065). For this research, the samples chosen to make the average were confined to the 3-7th century site of Veh Ardašīr as they are closest in date to the Islamic period.

Mirti *et al* (2009, 1063) recognised two broad groups within the flux elements as demonstrated in Figure 4.6. Sasanian 1 is a group with relatively low MgO (av. 4%), relatively high P_2O_5 (av. ~0.3%) and K_2O (av. ~3.3%). Sasanian 2, on the other hand, has high and variable MgO (av. 7.2%) and low P_2O_5 (av. 0.13%) and K_2O (av. 2.8%). The lime (av. 5.5% and 6.7%) is similar for both. The flux ratios (MgO/CaO and P_2O_5/K_2O) are clearly different (Table 4.2) indicating disparate plant ash compositions. These differences cannot be explained by processes such as ash washing or the heat/duration of ashing, and therefore must be related to either the geology of where plants grew or choice of plant species. For example, a longer ashing time and/or higher temperature would lead to a loss of compounds with lower boiling points, (e.g. K_2O) enriching the glass in those with higher boiling points (e.g. CaO, MgO, P_2O_5). Washing would lead to lower quantities of magnesia and lime in the glass and enrichment in Na_2O and K_2O, like that seen in Venetian *Cristallo* glass (McCray 1998). Neither of these processes

explain the variation between the glass groups, and in particular the differences in magnesia and phosphorus pentoxide. Sasanian 1 and Sasanian 2 inhabit different regions of Figure 4.6 and these regions are here designated Mesopotamian 1 and Mesopotamian 2 respectively. These designations denote the two principal plant ash types employed in Mesopotamian glass production during the Sasanian period and which also continue into the Islamic period.

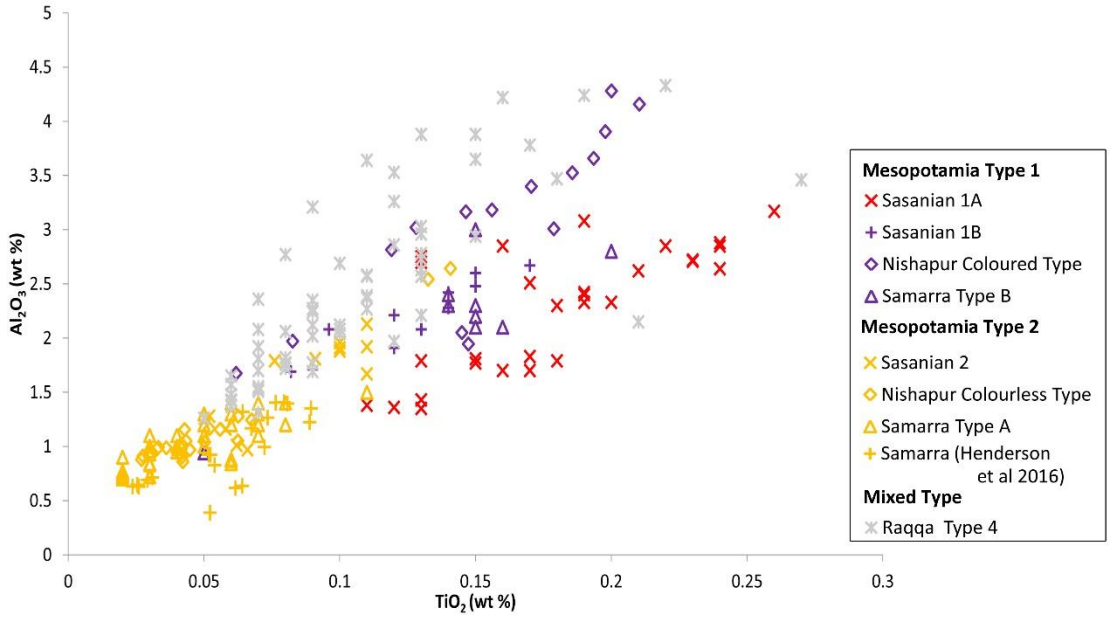


Figure 4.7. Comparison of the alumina and titania content for the glass groups of Mesopotamian origin demonstrating a closely shared ratio of values for most the glass groups, with separation seen in only the Raqqa Type 4 glass and Sasanian 1B. Also note the distinction between glass of Mesopotamian 2 group which contain a lower abundance of accessory minerals compared to Mesopotamian 1. Data sources as Figure 4.6.

For the silica sources Mirti *et al* (2009, 1066) recognised that the Sasanian 1 group splits into sub-groups A and B. Group 1A used a sand containing more accessory minerals, ZrO_2 TiO_2, Fe_2O_3, and a higher REE content than Group 1B, as displayed in Figure 4.7. Conversely, Group 1B matched Sasanian 2 in terms of the elements contributed by the sand. This led Mirti *et al* (2009, 1067) to suggest they share the same (or similar) sand source. This is best demonstrated by their corresponding Al_2O_3/TiO_2 ratios at 17.7 and 19.1, compared to Sasanian 1A with 12.8 (Table 4.2). Note, however, that while Sasanian 2 has analogous ratios to Sasanian 1B, absolute

quantities of accessory mineral elements are lower, indicating a choice of a purer but geologically similar sand source. This suggests the existence of two flux groups in close proximity but Mesopotamian 2 was selectively used with cleaner, impurity free sand and Mesopotamia 1 utilised with dirtier sand, richer in impurities. Isotopic analysis by Ganio et al (2013) added additional complexity to this picture, demonstrating that the Sasanian 1 and 2 glass groups were made at more than one production centre but within the same geological region, indicating several production sites. As a final note, Sasanian glass does not have added manganese oxide.

4.4.3.2 Nishapur and Samarran glass

Nishapur was a wealthy trading city in Northern Iran on the Silk route (Figure 4.3). The glass from this site shares close compositional similarities to Islamic glass from Samarra and Sasanian glass from Veh Ardašīr (Wypyski 2015) which implies a potential Mesopotamian provenance. Wypyski (2015) suggests production at Samarra, where glass working remains have been identified, though not fully published (Northedge and Falkner 1987, 149). Notwithstanding, glass production could have been located anywhere within this region. This is contra Kröger (1995) and Henderson et al (2016) who propose Nishapur as a glass working centre. A detailed discussion of the origins of Nishapur glass types is presented in Section 9.5 and will not be further discussed at this point. The Nishapur glass is dated to the 9-10th century and was analysed by Brill (1995; 1999A; B). Two compositions were recognised: Nishapur Coloured, which is a group of self-coloured and deliberately coloured glass, and Nishapur Colourless, a glass of high quality colourless fabric with a higher percentage of wheel-cut examples (Brill 1995, 212; Kröger 1995, 21). Average compositions for these types are presented in Table 4.1. The data used is LA-ICP-MS re-analysis by James Lankton (pers. comms) of samples described in Brill (1995). The vessels used for Nishapur Coloured was made of only the self-coloured samples. Furthermore, the cobalt coloured samples were formed into a separate group (Nishapur Co-blue; see Chapter 7). Average data is presented in Table 4.1.

The Nishapur Colourless type is a mainly well contained group made of glass with relatively high MgO (av. 4.7%), low CaO (av. 6.7%), K_2O (av. 2.5%), and P_2O_5 (av.

0.12%). It shares traits with Sasanian 2 group. Moreover, Nishapur Colourless type closely resembles the flux content of the Samarra Type A as from Samarra by Wypyski (2015, 130) and also Henderson et al's (2016) Samarra glass. These four glass groups share the Mesopotamian 2 plant ash type as demonstrated in Figure 4.5. The similarities between these groups suggest a shared production region using similar plants.

Nishapur Colourless glass has a high quality, clear fabric, characterised by low alumina (av. 1.2%). This has led Brill to suggest the use of quartz pebbles as a silica source (Brill 2012, 431), although low alumina is quite typical for plant ash glasses (Table 4.1). This glass type also contains low amounts of accessory mineral elements, titania (av. 0.05%) and iron oxide (av. 0.37%), although ZrO_2 (av. 73ppm) is relatively high. Comparison with the values of Samarra Type A and Henderson et al's Samarra glass in Table 4.1 indicates close corroboration (Figure 4.7). These groups, in turn, are similar to the sand component of Sasanian 2, again suggesting a shared geological origin.

The second type is Nishapur Coloured. This group shows close compositional similarity to Samarra Type B (Wypyski 2015). Nishapur Coloured is characterised by lower amounts of MgO (av. 3.8%), slightly higher K_2O (av. 2.9%), high P_2O_5 (av. 0.32%) and the same relatively low lime that is common to all Mesopotamian glasses (av. 6.7%). Nishapur Colourless and Samara Type B also have similar MgO/CaO and P_2O_5/K_2O ratios (Table 4.2). Both of these glasses fall into the Mesopotamian 1 (Figure 4.6), corresponding with the plant ash used for Sasanian 1 type glass. The plant ash for all three groups, therefore, is likely to be from a similar species and region.

For the silica source, Nishapur Coloured and Samarra Type B contained similar alumina (av. 3.05; 2.45%), titania (both av. 0.15%) and iron oxide (av. 1.12; 1.03%). These groups further match Sasanian 1B, although not the older Sasanian 1A. This overarching affinity between all the Mesopotamian glass can be seen in Figure 4.7 as demonstrated by their shared Al_2O_3/TiO_2 ratios. This implies a similar geological origin for the sands used during both Sasanian and Islamic periods, although Sasanian 1A shows greater differences. Fluvial sediments around the Tigris and Euphrates are reported to be very similar mineralogically (Minc 2016, 6), which might explain the similarities. However, while the accessory mineral ratios are similar, the absolute

quantities are not. Mesopotamian 2 flux was used with sand containing fewer impurities, possibly signifying an active choice in utilising certain plant ashes with particular sands.

Manganese was added to all of the Samarra Type B glass but only to some of the Nishapur Coloured glass. Nishapur Colourless and Samarra Type A contained low levels of manganese oxide, also intentionally added, but in low quantities. This variability in addition potentially suggests it was applied at the secondary production stage and that universal addition, evident in the Eastern Mediterranean glass, was not required – however it could also conceivably be that production was in smaller batches than that seen in Palestine and Egypt.

The interpretation of Raqqa Type 4 within this framework clearly demonstrates its similarities with Sasanian and Islamic glass from Mesopotamia as opposed to Syro-Palestine and Egyptian types (Figure 4.5). The two proposed end-members of Raqqa Type 4 correlate with the Mesopotamian 1 and 2 plant ash groups. The similarities imply the application of similar raw materials as Sasanian and Islamic Mesopotamian production. The sand elements plotted in Figure 4.6 indicate a correlation between Nishapur Colourless/Sasanian 2 and Nishapur Coloured/Sasanian 1B, although with slightly higher Al_2O_3/TiO_2 ratios for an exact match to either. The differences seen in alumina could represent potential variations of content along the Euphrates, which might equate to different production locations.

4.4.3.3 Summary

The Mesopotamian region appears to contain two principal flux types based on plant ashes from two different sources and/or species in use during the Sasanian and Islamic period until at least the 10th century. These have been termed Mesopotamian Type 1 and Mesopotamian Type 2. Continuity between Sasanian and Islamic glass production in their raw materials and production regions has been demonstrated. At least three separate sand sources are identified, of which Sasanian 1A and 1B used two compositionally different sources with differing mineral mixes, while the other groups used a sand with very similar Al_2O_3/TiO_2 ratios, but varying absolute elemental

quantities which reflect differing silica/accessory mineral mixes. Of these, sands with lower impurities tend to be preferred for the Mesopotamian 2 flux type. Finally, the two potential end-members of Raqqa Type 4 match the Mesopotamian 1 and 2 flux groups, additionally indicating similarities in sand sources, although with a marginally higher alumina portion.

4.4.4 Regional Plant Ash Groups: Conclusions

The analytical work so far performed on plant ash glass has enabled the identification of three broad plant ash compositions as outlined in this chapter. This included a compositionally tight, low MgO, high CaO, group produced in Syria, Palestine and Egypt termed Eastern Mediterranean Type; and two groups from Mesopotamia, defined as Mesopotamian Type 1 and Type 2, the former with lower MgO and higher P_2O_5, and the latter, with higher MgO and lower P_2O_5. Both groups had low CaO and the Mesopotamian glass displayed a much higher degree of compositional variation absent in Eastern Mediterranean plant ash glasses. Certain similarities between Sasanian and Islamic glasses of Mesopotamian origin indicate a continuity of production traditions and raw material usage. Elements within the sand has demonstrated compositional separations not visible using flux elements alone, with Egypt glass containing more zirconia, titania and iron oxide than that from Tyre and Raqqa, while a single sand geology appears to link the Mesopotamian Islamic glasses. This implies that production appears to occur in Mesopotamia within a certain geological zone and that sands with similar accessory minerals were utilised, however, absolute quantities of accessory minerals in the sands varied. Furthermore, the addition of manganese oxide occurred in both regions in the Islamic period, but to a much lesser extent in the glass from Mesopotamia, and not as all in Sasanian glass. This could be due to the different raw materials and that Mesopotamian glass may not have required decolouring or fining in the same way as Eastern Mediterranean glass did. It could also a reflection of preferred tastes in colour, or a lack of availability of manganese oxide in Mesopotamia.

CHAPTER 5

Methodology

This chapter will describe the methodologies used in this project. It will consist of five sections: i) explanation of the theoretical framework in which this project will be situated; ii) discussion of the sampling criteria, dating and description of the sampling sites; iii) description of the analytical procedure, data processing and statistical techniques; iv) justification of the techniques and a discussion of the validity of the resultant data and finally, v) description of element distribution within the glass raw materials and their usefulness for provenance.

5.1 Theoretical Framework

This project aims to answer questions concerning technological and organisational change. These are major themes in archaeology and are subject to a number of theoretical systems and frameworks in which changes can be explained and examined. This first section will explain the frameworks in which this project will be situated. It will present the principal theories on how technological change occurs and discuss the drivers of innovation and technological adoption. It will also consider models of organisation of production, trade and economy, and explain how these affect the interpretation of data.

5.1.1 Introduction to Technological Change

Early Islamic Palestine was a complex society where the processes of technological change were conceivably affected by a variety of social, cultural, political, economic, as well ecological and material factors. A good overview of the contribution of archaeological science to theory is given in Martinón-Torres and Killick

(2015). Killick (2004) recognised three main systems of theory governing technological change, each with their own core values and working frameworks: behaviouralists, Darwinian evolutionary archaeologists and social constructivists. Behaviouralists examine change and variability in human society through the investigation of the relationship between people and artefacts (Schiffer 1995; 1996; Schiffer et al 2001; Longacre and Skibo 1994). Technological change is seen to occur in a number of ways: through trial and error in order to solve practical problems; adaption of the function of an object; or through consumer (market) pressures (Schiffer and Skibo 1987, 598), which are themselves subject to a number of theorised models (see Schiffer et al 2001, 732). Whether a technology is adopted depends on its benefit, known as performance characteristics, which are compared using a performance matrix framework (Schiffer 2004; Schiffer et al 2001, 733). Behavioural archaeology has been used to investigate and describe the development of 19th century electric lighthouses (Schiffer 2004) and changes to tempering technologies in ceramics to increases pot durability (Schiffer and Skibo 1987). Darwinian evolutionary archaeologists (Basalla 1988; Shennan 2013; Kingery 1993; Kuhn 2004), on the other hand, describe technological change through random variations (Shortland (2004A) describes these as *'mutations'*) with only the beneficial technologies being adopted through a process of '*natural selection'*. The process of change is therefore random but the choice of which innovations are adopted is linked to concepts of optimality and efficiency. Evolutionary models have been useful in explaining advances in iron smelting practices (Charlton et al 2010), developments in ceramic styles in Neolithic Europe (Shennan and Wilkinson 2001) and variability within lithic artefacts (Eerkens and Lipo 2005) among others.

The final approach is the social constructivist position, which is, in essence, more a collection of concepts rather than a distinct system of theory. For Killick (2004, 571) a social constructivist is someone who agrees that more than one technology is able to satisfy a given task, and that, in these cases, technological choice is influenced by social and cultural considerations. He proceeds to explain that the social constructivist position holds that *'no explanation of an observed technological change is complete unless it relates to the choices… made by actual human beings'* and explanations solely relying on concepts of *'selection, market forces, adaption or the inevitability of*

progress' are to be dismissed. Within the social constructivist approach lies a number of concepts directly relevant to this project: technological choice (Lemonnier 1993, Gosselain 1998; Sillar and Tite 2000); technological style (Lechtman 1977; 1984; Childs 1991; Hosler 1994); agency theory (Dobres 2000; Dobres and Robb 2000); and materiality (Jones 2002; 2004). A contextualist approach, similar to that espoused in social constructivism, has been used with success to investigate technological change in other complex societies (e.g. Bijker and Law 1992; Lemonnier 1993; Van der Leeuw 1993; Lavan 2007; Greene 2007; Hjärthner-Holdar and Risberg 2009). This project, due to the high levels of social complexity within Early Islamic Palestine, will adopt a number of the frameworks held within the social constructivist system but will nevertheless also take into consideration some of the more functionalist ideas prevalent within behavioural archaeology.

5.1.2 Frameworks of Technological Change and Adoption

One of the principal frameworks will be the use of the chaîne opératoire. The idea was first conceived by Mauss in the study of lithic artefacts (Mauss 1941), but coined by Leroi-Gourhan (1964), and has recently been more fully defined and expanded via Lemonnier (1992) and Schlanger (1994; 2005). The chaîne opératoire is a straightforward yet powerful tool with which to study artefact production and use. Schlanger defines the chaîne opératoire as the "*range of processes by which naturally occurring raw materials are selected, shaped and transformed into useable cultural products"* (2005, 25). By considering production in a sequence it permits the critical examination of the choices involved, allowing the physical constraints to be identified, and the choices due to social/cultural factors isolated and examined. As Schlanger explains, the chaîne opératoire provides *a "rigorous methodological framework for reconstructive processes of manufacture and use"* (ibid, 26) which allows the fixed operations *('strategic tasks'* after Lemonnier 1992) to be separated from the choices, which are socially and culturally relevant. In the present study, using the framework of chaîne opératoire will require a critical understanding of the processes of glass production, starting from the raw materials, through the process of primary production, trade, secondary production, distribution, consumption and recycling. The

interpretation of the results will rely on this framework and will enable the identification of choices.

The concept of choice is critically important and is contained within the framework of technological choice (Lemonnier 1992; 1993; Gosselain 1998). Sillar and Tite (2000, 2) comment that technologies *"can be analysed as cultural choices"* and depend on their social, economic and ideological setting, as well as more functional criteria. They make the distinction between the direct influences (material and physical constraints) versus the indirect influences (social and cultural considerations). It is these latter changes that inform about a society, and it will be through the identification and separation of choice that the drivers of change will be identified. Technological choices are additionally constrained by what a producer knows and has been taught, this is his cultural and environmental context, and this leads to a development of what Lechtman (1977) called a "*technological style*." Different glass producers used different technologies, which were thus constrained by their knowledge, environment and their social and cultural context. Using these frameworks will allow the recognition of choice and also facilitate the separation of different technologies by their inherent technological style.

Of the mechanisms of technological change discussed above, evolutionary change is unlikely to be a factor in this time period. Evolutionary change is untargeted and slow, progressing in small variations over long periods of time. Palestine was a complex society in which innovation would have had drivers, such as economic pressures. Processes such as experimentation, which might have been driven by the need for new, cheaper, raw materials, or the adoption of new technologies through diffusion (knowledge transfer), might have been of more importance in creating technological change. These processes were then aided or constrained by other considerations such as the speed of adoption. Adoption is the process by which technology is taken up within a society, and it has been observed that, according to what Greene (2007, 667) names the Edgerton principle, that *"innovation may experience their greatest diffusion in very different contexts from those of invention",* meaning that the greatest use of an idea doesn't necessarily follow its invention but requires a reason or driver, for its adoption. Adoption depends on other socio-cultural and contextual factors, with

Greene (2007) giving the example of lead-glazed pottery in the Late Hellenistic and Early Roman Empire. Lead-glazing had certain functional advantage over unglazed ceramics, however, for culturally specific reasons lead glazing, while known, was never adopted. Greene puts this down to the dominance of glass in Roman society, which made glazing technologies superfluous.

Similarly, Shortland (2004A) finds the same lack of a driver for the adoption of glass on a large scale in Bronze Age Egypt. Only in later periods, with a demand for cheap substitutes for semi-precious stones, did an economic imperative appear and glass become used on a more common basis (ibid, 10). Sherratt and Sherratt (2001) gives another example of glass production in Bronze Age Egypt stimulated by a need for *'import substitution'* and a cheaper alternative to lapis lazuli. These examples link to the materiality of glass and how societal perceptions of a material can affect which technology is adopted. Adoption only occurs when a society or market desires an object or material, whether this is due to a certain religious or cultural niche, or an aesthetic prevalent in society at that time. Uptake of new glass recipes in Early Islamic Palestine may well have followed changes in Palestinian society, potentially linked to growth in Islamic identity, or may have had economic drivers, such as a need to revert to cheaper raw materials. Furthermore, Shortland (2004A) describes how adoption can be constrained or accelerated by different groups in society, this he calls diffusion of innovation theory (DOI).

Technological transfer itself is not a straightforward process, even in societies demonstrating written communication (Laudan 1984; Kelly and Krazen 1978), with person to person contact being the most efficient. Innovation and the diffusion of a technology is therefore stimulated by the movement of people for trade or of craftsmen. Such movement has been implicated in stimulating the Bronze Age Egyptian glass industry where state owned workshops used foreign workers resulting in a transfer of glassmaking technology (Moorey 2001). Sherratt and Sherratt (2001) also comment on the importance of having an open economy with the free movement of trade, especially where the choices of consumers themselves generate a want for technological change. Strong trade in early Abbasid Palestine, as well as the

concentration of workers in industrial zones, would have facilitated this form of knowledge transfer.

Finally, it should be noted that there are always ecological constraints on a technology. The availability of raw materials, e.g. suitable flux and sand sources, will affect what types of glass making technology are viable. For example, the failure of the adoption of glazing in Bronze Age Egypt is likely to have been as much due to its incompatibility with local Nile clays, as due to the social and cultural circumstances at the time (Paynter and Tite 2001).

5.1.3 Models for Production Organisation and Trade

This project uses compositional data to inform on the organisation of the glass industry. This will encompass the types of raw materials, the number and location of production sites where identifiable, and the investigation of these locations in respect to the consumption and discard sites of the glass. Recycling will also be examined in order to investigate the quantities of 'fresh' glass in circulation. The use of compositional and contextual data in conjunction with comparisons to glass of known types and from known production sites will enable details of the glass industry to be investigated. However, without a framework to aid analysis of these data, the information cannot be fully utilized and interpretations cannot be robustly made.

The current model for the organisation of natron glass production during the Roman and Byzantine period has already been mentioned in Chapter 3. Production is recognised as using a centralised production model. Whereby large quantities of glass were made at one site. Raw chunks of glass were then traded for shaping vessels at a greater number of secondary sites/workshops, the shaped glass was then distributed locally or regionally (Freestone et al 2002A). The alternative to this model is the dispersed workshop model. Here glass is made at a workshop and shaped into vessels at the same location. Both stages (glass making and vessel shaping) are performed at a single site. The vessels would then be traded locally or regionally in an area around the workshop with trading distance most likely dependent upon the value of the products. The workshops will be frequent and well distributed, allowing the region to be

supplied with vessels. This model is seen in the glass industry of medieval Europe (Willmott 2005) and in the pottery industry of Early Islamic Palestine (Walmsley 2012). Higher quality (more valuable) vessels may travel farther distances, inter-regionally or even internationally, and this is also true for vessels that may hold tradable commodities, such as perfumes or foodstuffs, as demonstrated from the movement of amphorae (e.g. Pieri 2012; Williams and Peacock 1986).

A centralised industry would suggest large scale production, what Peacock terms nucleated workshops or manufactory using terminology from Roman pottery production (Peacock 1982, 6-11), while a dispersed model would suggest smaller scale manufacture, such as individual workshops. Although due to the technical nature of glass production and the requirements for certain raw materials, household production would be unlikely. As noted in Chapters 3 and 4 there is as yet no evidence for production at estates, or for the state organisation of glass production, although glass production at Raqqa might be a contender for the latter.

In summary, the two models of centralised and dispersed production will form the framework in which the compositional results will be tested. Each of these models imply differences in the scales of production and in the patterns of glass distribution, which can also be investigated.

The movement of glass within and between regions is also influenced by economic and trade models. Islamic Palestine is recognised as a monetised society with an operating market economy (see below). Different types of trade are well discussed in the archaeological literature (Polanyi 1957; Renfrew 1975) with three principal trade types being recognised: reciprocity or gift exchange; redistribution by elite persons or authority; and trade for profit by marketing. The second of these was of particular importance during the Roman and later Byzantine periods as demonstrated by the distribution of amphorae. Williams and Peacock (1986) give examples of both the Annona system of grain distribution and the supplying of the armies (ibid, 57-58), and also note the influence of the church in the mechanisms of supply in later periods (ibid, 59). Distribution in a market economy would be determined by the costs of transportation and by the distribution of people that are able to afford the goods, and would therefore lead to a *'fairly diffuse'* spread of goods across an economic zone

above a certain wealth level (ibid). Redistribution on the other hand would be more specific and directed at certain people with special privileges or needs, and therefore would point to a *"restricted geographical spread of finds"* (Williams and Peacock 1986, 61-2). In early Islamic Palestine investigations of the distribution of mid-high quality ceramics show a dispersed distribution in a 30-50km area around production centres (Walmsley 2012), and up to 100km away in rare instances, possibly as a result of secondary trading. These studies suggest that ceramics were traded locally through markets and their distance of travel from the production site was based on their value, implying trading for profit. Larger scale interregional and also international trade networks are also recognised in this period, as described in Goitein (1967; see Chapter 2). Goitein (ibid), using evidence from the Cairo Geniza, provides ample evidence of long distance trade by sea and overland between Palestine and Egypt in the Islamic period, as well as to other locations around the Mediterranean and beyond. This trade is also evidenced from ceramic distributions (McCormick 2012).

In addition to ceramic evidence, other sources attest to a market economy operating in Palestine. McCormick (2012, 55) identifies three different *"modes of economic behaviour"*. The first is '*instrumental*' mode in which individuals act to maximise the returns of an economic activity. This mode is the closest to *'market exchange'*. Next is a *'traditional'* mode, which is reciprocity, here market forces are not a significant driving force. And finally, *'command'* mode, in which the market is controlled hierarchically with prices and actions governed by the state. McCormick argues for the existence of a market economy in Egypt from the 4th to 11th century by providing examples of the recording and use of market information (ibid, 60) to inform on selling price and to instruct trade. This is backed up by Goitein (1967) in which the letters of the Cairo Geniza indicate a dynamic economy in which business men and traders were acting to maximise profits by responding to changing commodity prices (e.g. ibid, 219-221). It is evident that an instrumental mode of economic behaviour was being used, and that prices were being driven by the market through supply and demand, and other associated costs, and not artificially or otherwise controlled. Banaji (2010) goes even further to suggest that businessmen of the Abbasid period were operating at the level of *"pre-modern capitalists"* through the reinvestment of profits back into

businesses (ibid, 175-6). The Islamic period was also a monetised economy, which is important for the trade of goods, as is discussed in Shatzmiller (2011). The evidence presented here suggest that Palestine and the Islamic Caliphate was a market economy with instrumental modes of behaviour in operation and that market pressures would have had an effect on glass production and trade.

5.1.4 Summary

This project takes a contextualist approach and attempts to categorise the many differing factors influencing technological change in glass-making during this particular period. This examination will use a number of different frameworks within the social constructivist system, namely the use of the chaîne opératoire, technological choice and style, and materiality, but will not ignore ecological constraints, nor economic and efficiency drivers of change. In the understanding of the organisation of the industry a framework provided by Freestone et al (2000; 2002A), along with transport and trade models (Polanyi 1957; Renfrew 1975) and with the understanding that the Caliphate was operating as a market economy will assist the interpretation of data.

5.2 Sampling and the Sample Sites

The data generated in this project comes from compositional analysis of glass samples taken from excavated sites in Israel. The research questions are specific but broad and reliant on the recognition of general trends operating in the region over a long-lasting chronological period. To answer these questions a large range of representative samples were selected utilising a number of sampling criteria.

5.2.1 Sampling Criteria

Analysis was confined, where possible, to vessel glass and deliberately eschewed other glass products, e.g. beads, bracelets, windows. A small number of exceptions do

occur, e.g. stirring rods (TIB 5583-02; AY 2989-02). The reasoning behind this decision was to ensure that the scope of this project was, to the greatest degree possible, restricted to the understanding of the chaîne opératoire of a single glass industry. Beads or window glass might follow a separate chaîne opératoire through the use of different raw materials, recycling practices, production organisation or glass procurement. Moreover, vessel glass has certain advantages, being ubiquitous, constituting the majority of excavated glass, and diagnostic pieces are more easily dated.

The chosen samples are representative of vessel glass in common use taken from consumption sites only. Waste from workshop or primary production sites were not investigated. The aim is to investigate the glass industry by looking at the glass in circulation, waste from production sites and workshops is by its very nature, discarded material and may, therefore, not be truly representative of the finished product. Glass taken from furnace remains may also suffer from contamination. In terms of the types of vessel, sampling targeted common forms in order to obtain a representative range. Samples are mainly domestic – bowls, bottles, beakers –, although a few unique or unusual items, such as horseshoe shaped objects (RAM 3592-02, RAM 4740-01), a horn (RAM 4768-06) and elongated bottles (JER 3835-07, RAM 6297-05), were also selected. The vessels are predominately undecorated, but a range of decorated types are also present. Furthermore, colouring elements (transition metals + associated impurities) would dilute and alter the base glass making compositional groups harder to distinguish. Therefore, deliberately coloured vessels, such as opaque glass or vessels with added lead or copper, were avoided. There are two exceptions to this rule, cobalt-coloured and manganese decoloured glass are permitted. Cobalt-coloured glass is frequent enough and quantities of added cobalt low enough that meaningful groupings can still be created, while manganese oxide is an almost universal additive in Islamic glass plant ash glass and is therefore an important and unavoidable aspect of production.

Another requirement of the project is that the glass analysed is, where possible, representative of the region. Consequently, a range of sites were chosen from across Israel. The designated sampling sites were contextually varied encompassing different

social, cultural and economic settings. For example, material was taken from two regional capitals; Ramla, a newly founded Muslim city and Tiberias, a city with a mainly Jewish population; an urban port city of Caesarea; the large inland urban cities of Bet Shean, Jerusalem and Sepphoris; two military forts of Ashdod Yam and Ha-Bonim; and three smaller rural settlements, of Ahihud, Tel Rosh, and Nahal Shoval. These sites, as discussed in Chapter 2, cover a large geographical spread of the country.

Finally, dating was of paramount importance (further detailed below). The dating resolution was to be as fine and accurate as possible, as well as providing an even spread of samples across the approximately five century time period. The samples were procured from controlled excavations undertaken by the Israel Antiquities Authority (IAA). Glass was selected, where possible, from secure contexts, with dating aided by associated ceramic and coinage, while the use of mainly diagnostic fragments informed on date through typology, style, decoration and fabric. Typological dating through glass is well advanced in this region (see Gorin-Rosen 2010A; Hadad 2005). The date range for this project covers Late Byzantine/Islamic transition to the beginning of the Crusader period, 7th to 12th century, although some samples date to the 13th century (particularly material from Bet Shean). It was intended to get an even distribution from across this time period. The widest continuous chronological spreads came from the larger urban sites of Ramla and Jerusalem, covering multiple centuries. The smaller excavations and sites – Ahihud and Bet Shean – had more specific chronological ranges.

5.2.2 The Samples

A total of 292 glass samples were taken from 19 excavated sites from 11 locations (Figure 5.1) following the criteria discussed above. Sampling was performed at the IAA stores in Jerusalem under the guidance of Yael Gorin-Rosen, Head of the Department for Glass. Sample collection was performed in two stages, the first in May 2013 with the collection of 96 samples from six excavations; Ahihud, Bet Shean, Ramla (Licences A-4740; A-4768; A-5947) and Sepphoris. The second stage was in November 2014 when 196 samples were collected from a further 11 excavations: Ashdod Yam,

Caesarea (W2S3; A-6194), Ha-Bonim, Jerusalem (A-3825; A-5125), Nahal Shoval, Ramla (A-3592; A-3897; A-6297; A-6490), Tel Rosh and Tiberias.

Figure 5.1. Map of modern day Israel with sampling sites marked and labelled.

Each glass fragment was photographed before a small piece was removed using wire cutters or pliers. Pieces were scored using a glass cutter if required. Sample size was typically 5mm. Site licence, loci and basket number were recorded for each fragment, and each was linked to a drawing within the published or pre-publication literature where available. Export permits were provided by the IAA before the glass samples were shipped to the UK.

5.2.2.1 Dating

The dating of the glass samples was principally via typology and fabric first, the date was then further constrained with reference to sample context and stratigraphy. The use of ceramics and coin finds in association with glass containing contexts helped to increase the precision of the dating, narrowing the potential date range. The typological dating of these vessels came primarily from publication or pre-publication reports written by glass specialists at the IAA (see Table 5.1). Further information on published and unpublished pieces, as well as guidance, was provided by Yael Gorin-Rosen, with additional information from IAA glass specialists Tamar Winters, Natalya Katsnelson and Brigitte Ouahnouna.

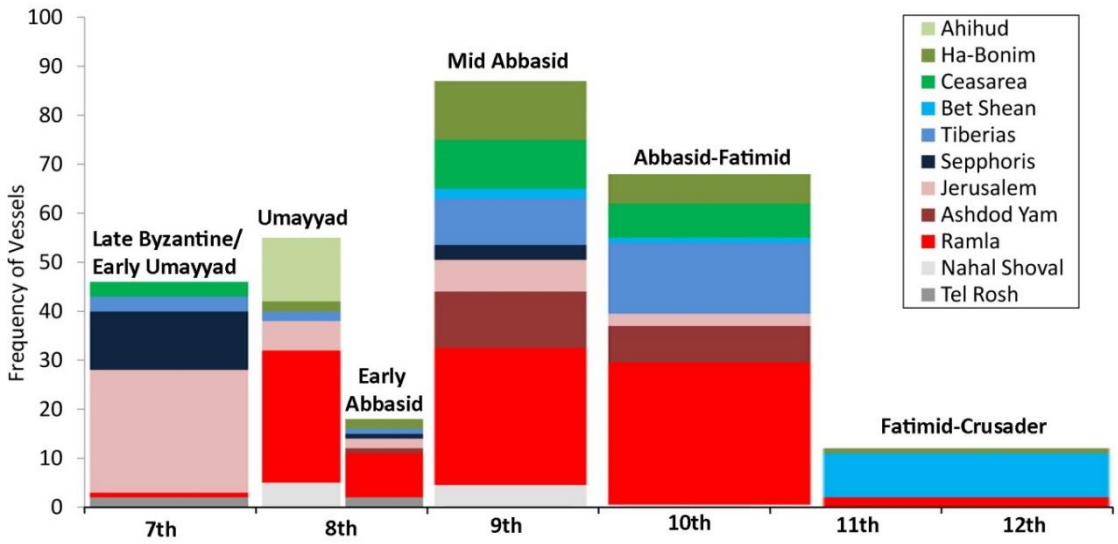


Figure 5.2. Vessel frequency sorted by date and sampling location.

The dating of the samples was split into six dating categories; Late Byzantine-Umayyad (7th); Umayyad (early-mid 8th); Early Abbasid (mid-8th-early 9th); Mid Abbasid (9th-10th (but also probably includes material from late 8th); Abbasid-Fatimid (10th-early 11th) and Fatimid-Crusader (mid-11th-13th). A break-down of vessel dating by site is given in

Table 5.1. List of the sampling sites with site license, numbers and site report references.

Location	Site	License/Area	N	Date range	Excavation report	Glass report
Ahihud	Moshav Ahihud	A-3746	13	8th-13th	Porat and Getzov 2010	Gorin-Rosen in Porat and Getzov 2010
Ashdod-Yam	Ashdod-Yam Castle	A-2844; A-2989; A-2658	22	late 8th-13th	Raphael 2014	Ouahnouna 2014
Bet Shean	Youth Hostel	A-2885	12	late 8th-13th	Sion 2000A; Sion 2014	Katsnelson 2014
Caesarea		A-6194	15	9th-early 11th		Gorin-Rosen forthcoming A
	South Western Zone	Insula W2S3	4	7th-10th		Winter forthcoming A
Ha-Bonim	Ha-Bonim Castle	A-3032	23	8th-11th	Barbé et al 2002	Katsnelson forthcoming A
Jerusalem	City of David Giv'ati Car Park	A-3835	15	late 6th-11th	Shukron and Reich 2005; Ben Ami 2008; 2013	Winter forthcoming B
	The Old City: Wilson's Arch and Great Causeway	A-5125; A-5570	31	7th-11th	Onn et al. 2011	Katsnelson forthcoming B
Nahal Shoval	Nahal Shoval	A-6362	10	8th-11th	Daniel 2005	Winter forthcoming C
Ramla	Ramla	A-3592	6	7th-11th		Gorin-Rosen forthcoming B
	Danny Mass Street	A-3897	8	10th-11th	Shmueli 2012; 2016	Katsnelson 2016
	Ma'asiyaha Junction	A-4740	13	8th-13th	Haddad 2013	Gorin-Rosen 2013
	Lod-Na'an railroad track	A-4768	11	8th-late 11th	Haddad 2010	Gorin-Rosen 2010B
	Ha-Nevi'im Nursery School	A-5947	31	8th-12th	Haddad 2011	Gorin-Rosen 2011
	Ha-Etzel Street	A-6297	16	8th-11th	Toueg 2013	Winter 2013
	Ha-Hez Street	A-6490	12	8th-early 11th	Toueg and Torgë 2015	Winter 2015
Sepphoris	Moshav Zippori	A-3791; A-3821	16	7th-10th	Tepper 2010	Gorin-Rosen 2010C
Tel Rosh		A-6055	4	7th-9th		Winter forthcoming D
Tiberias	Roman Theatre	A-5583	30	7th-11th	Atrash 2010	Gorin-Rosen forthcoming C

Table 5.2. The numbers of vessels of each dating category for locations. Note that samples dated to the 9th-early 11th date range are averaged across the 9th-10th and 10th-early 11th date categories.

Period	Date	Ahihud	Ashdod Yam	Bet Shean	Caesarea	Ha-Bonim	Jerusalem	Nahal Shoval	Ramla	Sepphoris	Tiberias	Tel Rosh	Total
Late Byzantine/Early Umayyad	7th	0	0	0	3	0	25	0	1	12	3	2	46
Umayyad	early 8th	13	0	0	0	2	6	5	27	0	2	0	55
Early Abbasid	mid 8th-9th	0	1	0	0	2	2	0	9	1	1	2	18
Mid Abbasid	9th-10th	0	11.5	2	10	12	6.5	4.5	28	3	9.5	0	87
Abbasid-Fatimid	10th-early 11th	0	7.5	1	7	6	2.5	0.5	29	0	14.5	0	68
Fatimid-Crusader	11th-13th	0	1	9	0	1	0	0	3	0	0	0	14

Table 5.2 and in Figure 5.2. While great care was taken on the accuracy of the dating it is inevitable there will be overlaps between these groups due to misdating of long-lived forms, curation of vessels in which earlier vessels appear in later contexts (for example RAM 3592-01) or simply due to a lack of adequate detailed information. Consequently, in certain cases choices had to be made. For example, most samples from Wilson's Arch, Jerusalem (JER-5124; discussed below) were identified as typologically 7-8th Late Byzantine-Umayyad (Katsnelson forthcoming B), meaning they could be 7th or 8th century, however the appearance of some earlier forms (wineglass JER 5124-11; trailed decoration JER 5124-11) and fabrics more similar to earlier dates meant that these samples were given a 7th century date, but it is possible that some of these vessels continued in use into the early 8th century. This contrasts with vessels from Ramla which have an 8th century and later date due to the founding of Ramla in c. 715 giving a *terminus post quem* for the Umayyad glass. In other cases, choices had to be made with long-lived types, for example, AY 2989-05 (Fig. 5.6c) was a type that first appeared in the Umayyad period but was most common in the Abbasid period, this dating, along with its context, meant that this piece was given a 9th-10th century date rather than earlier.

A large quantity of long-lived forms dated to the 9th-early 11th century. This is particularly apparent in material from Tiberias, but also some samples from Caesarea. This time range covers the 9th-10th and 10th-early 11th dating categories. In this case the vessels are averaged evenly across both date groups; this will be taken into account in the discussion. Also note that there is liable to be overlaps in dating between the 10th-early 11th century and the 11th-13th century groups. The types described as 'Serçe Limanı' (see vessel descriptions Appendix C) are placed in the 10th-early 11th date group. Vessels described as Crusader, Ayyubid and Mamluk are categorised into the later 11th-13th date group.

Finally, the late 8th century category needs particular explanation. This group contains samples which are identified as Umayyad-Abbasid or Early Abbasid types, or which can be identified from specific contexts (e.g. AY 2989-01, HB 3032-03, 04), nevertheless, this is not a definitive group and it is likely that this group overlaps with the 9th-10th century glass, and vessels present in the 9th-10th century could have originated in the

late 8th century. Therefore, while this time period seems to have fewer vessels, this is artificial. Moreover, this statement is equally true for the entire vessel selection; any differences in absolute quantities of glass between dating groups is due to sampling strategy and choice of site and cannot be taken as representative of quantities of glass available in that period.

Individual sample information, including description, photograph and drawing (where available), as well as contextual information (site, context, colour, dating) can be found in Appendix C and D.

5.2.3 Sampling Sites

This section describes the archaeology of sample excavation sites. A more general history of the sites is provided in Chapter 2. The sample site locations are displayed in Figure 5.1 and sample details with date range, excavation and glass report references are shown in Table 5.1. Note that the sites are identified in the site excavations by their Permit or Licence number, e.g. A-3746 for the excavation at Ahihud. These numbers will be used to aid identification so that sites can be better identified to that listed in the literature, such as the IAA online publication *Hadashot Arkheologiyot: Excavations and Surveys in Israel*. Figures 5.3 to 5.8 give examples of vessels from each location sorted by date category.

5.2.3.1 Ahihud

Ahihud was a small rural settlement 9km east of Akko. The samples came from a salvage excavation (Permit A-3746) in 2002 supervised by L. Porat (Porat and Getzov 2010). Trenches were opened up at area D exposing a number of buildings and some agricultural installations, including a Byzantine olive press. The glass finds came from stratum D2, a later phase overlaying the olive press. The glass is described and dated by Gorin-Rosen (in Porat and Getzov 2010). Thirteen vessels were sampled, these included bowls, wine glasses and lamps. The vessels were Late Byzantine/Umayyad

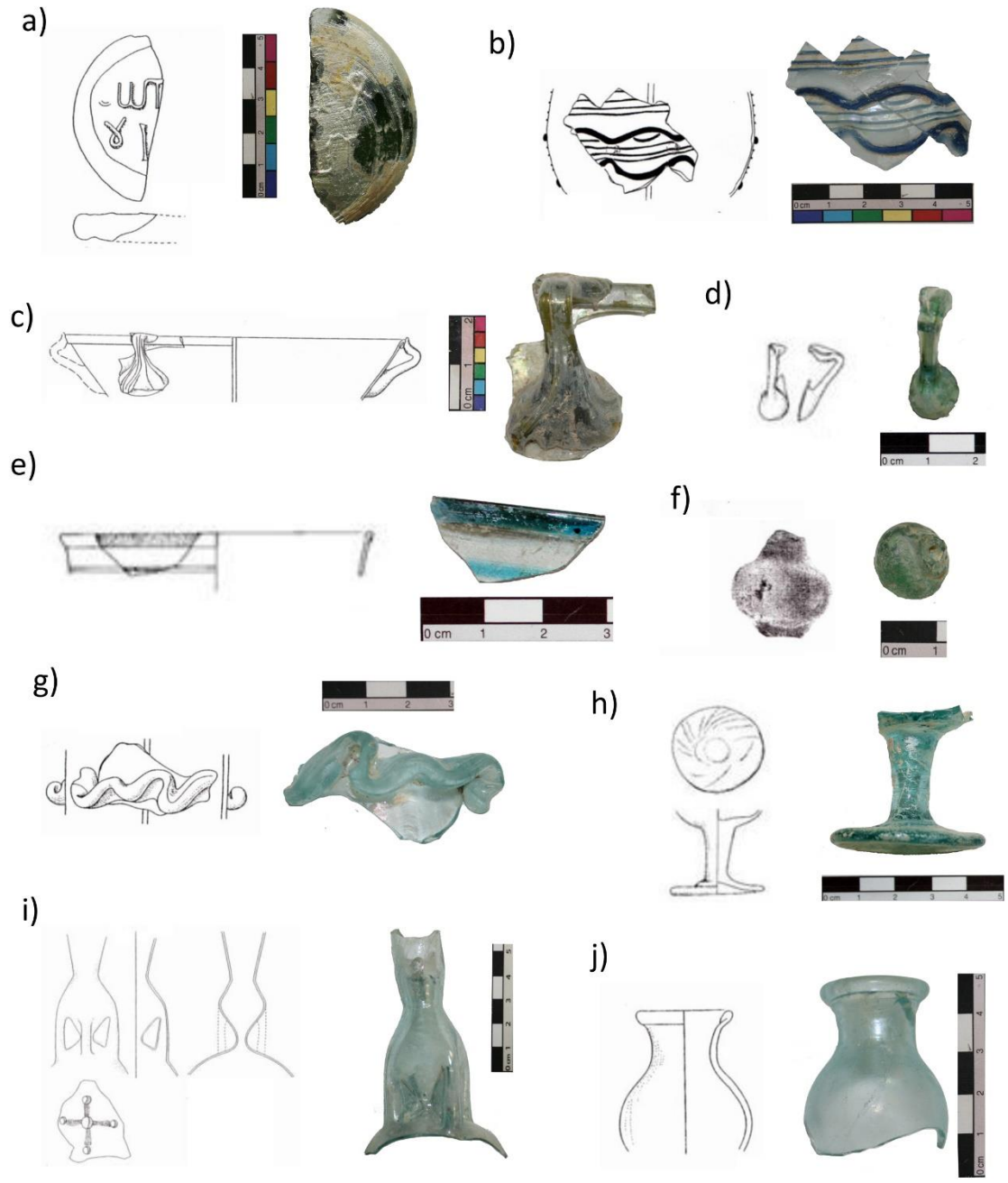


Figure 5.3. Examples of vessels dated to the Late Byzantine-Umayyad period, 7th to early 8th century. a) CEA W2S3-01; b) JER 3835-03; c) JER 3835-01; d) SEP 3791-10; e) SEP 3791-05; f) RAM 3592-01; g) JER 5124-02; h) SEP 3791-12; i) JER 5124-04; j) JER 5124-02.

types but the dating was refined by the ceramic dating of stratum D2 to the early 8th century Umayyad period (Figs. 5.4a, b, c). Principal colours were pale blue to greenish blue, with tonged and pinched decorative types. Some production waste of raw glass and furnace lining was recovered from these contexts. Adjacent excavations (Cohen

2007; 2008; Avshalom-Gomi 2009) found further buildings, some industrial activity (pottery kiln, wine press) from the Roman, Byzantine and early Islamic periods, as well as a number of later 15th/16th century buildings, but no additional glass.

5.2.3.2 Ashdod Yam

The Umayyad fortress of Ashdod Yam was built by 'Abd al-Malik (685-705 CE) in the late 7th century on the site of a Byzantine settlement. The site was subjected to three seasons of excavation – Permits A-2844, A-2989 and A-2658 – published in Raphael (2014), with the glass published by Ouahnouna (2014). In total 4800 glass fragments were recovered, 60% of which was undiagnostic, and 51 vessels dating from the Umayyad to Fatimid period were published. 22 samples were sampled for this thesis, taken from across the site. The vessels were domestic types – mainly bottles, bowls, a lamp and jug. Forms are decorated, which includes tonged, mould blown, trailed and also wheel cut types. For example, a wheel cut molar flask (AY-2989-08) and a miniature bottle (AY-2989-09). There was also a stirring rod (AY-2989-02). Dating was performed using typology and style, putting the date range of the vessels to the 8th to 11th centuries. A single sample (AY 2989-01; Figs. 5.5b) dated to the Umayyad-Abbasid transition of the late 8th century, eight samples to the 9th-10th century (Figs. 5.6a, b, c), four to the 10th-11th century, some of which are Serçe Limanı types, e.g. AY 2844-06 (Figs. 5.7a, b), and a further seven samples dated to the 9th-11th century, split evenly over both date groups. A final sample (AY 2989-15; Fig. 5.8a) was identified as a later type, possibly Ayyubid-Mamluk and was put into the 11th-13th century date group. Vessels fabrics were generally colourless or greenish, but with two coloured samples: a dark green molar flask (AY 2989-09) and a blue bottle (AY 2989-16). These were found to be lead glass and copper coloured respectively, and while the analyses are presented in Appendix K they are not discussed further here.

5.2.3.3 Bet Shean

The glass from Bet Shean came from a salvage excavation (Permit A-2885) just outside the eastern edge of the city on an area of land sloping down to the Jordan Valley. The

excavated site is described by Sion (2000A; 2014) who reports a small residential district of high status houses built during the Byzantine period outside the city walls overlaying an old Roman burial ground. The site consisted of four buildings occupied from the 6th century and abandoned at the end of the 10th, and then reoccupied during the 12-13th, before final abandonment during the Mamluk period. A total of 2000 glass fragments were found, dating from the late 3rd to 15th century as reported in Katsnelson (2014). 12 samples were chosen for analysis dated by typology and context to the Abbasid-Mamluk periods: two samples were late 8th to 10th century (Fig. 5.6d) and the remaining ten vessels dated to the 12th-13th century Ayyubid-Mamluk period (Figs. 5.8b, c, e). These vessels were found from buildings I-III and were a mix of everyday jars, jugs, bottles and bowls, but also some more high status items, for example a possibly mould blown jar of high quality colourless fabric (BSH 2885-12; Fig. 5.8e). Much of the later dated material came from a storage pit of Building I. Decorations included pinched and mould blown types, colouration pale-blue, green and colourless.

5.2.3.4 Caesarea

Material was taken from two sites at Caesarea. Fifteen samples were chosen for analysis from the first site: 4 from excavations under Permit A-6194 and a further 11 from an older site with no permit number. The glass is described in Gorin-Rosen (forthcoming A). One sample was dated to the 9th-10th century and the remaining 14 vessels dated by typology to the 9th-early 11th century, Abbasid-Fatimid period. These vessels are averaged over the 9th-10th and 10th-early 11th date categories. The vessels consist of mainly bottles and some beakers. Decorative types include tonged, mould blown and engraved techniques. The vessels are mainly colourless; however, three vessels have a rare colouration of a bluish glass with slight opacity (examples CEA 6194-03 and -09).

The second site was Insula W2S3 published in Winter (forthcoming A). This was a Byzantine period storage area and public bath in the South Western Zone of Caesarea (described in Porath 1996). A number of Early Islamic glasses were found, of which

Figure 5.4. Examples of vessels dated to the Umayyad period, early-mid 8th century. a) AH 3746-02; b) AH 3746-08; c) AH 3746-12; d) JER 5124-18; e) JER 5124-10; f) HB 3032-01; g) RAM 5947-01; h) NS 6362-01; i) NS 6362-02; j) RAM 5947-04.

four samples were taken: two samples dated to the 7th century (Fig. 5.3a) and two to the mid-Abbasid 9-10th century. The vessels are a large jug/jar/oil lamp, a stamped glass weight and two bottles, one of which was mould blown and the other a cobalt blue elongated bottle (CEA W2S3-04). Other vessels were greenish and pale blue in colour.

5.2.3.5 Ha-Bonim

Ha-Bonim was an Umayyad coastal fortress built at the end of 7th century by Abd al-Malik (r. 695-705; Vunsh et al 2013). The samples from Ha-Bonim come from Permit A-3032, excavated in 1999 and reported in Barbé *et al* (2002), a separate glass report is in preparation (Katsnelson forthcoming A). A number of areas were excavated covering both inside and outside the fort. A total of 23 vessels were sampled for analysis, 13 from Area 10 and 10 from Area 30. Area 10 was two vaulted rooms inside the castle. The lowest layers contained drains with Roman and Byzantine cultural material, this layer was overlain with the first building phase of the castle in the Umayyad period, producing a number of sealed contexts containing material of Late Byzantine/Umayyad transitional phase (*ibid* 32*; e.g. HB-3032-03 & -04). In total, this area yielded 164 baskets of glass, ranging in date from the Late Roman to Mamluk but primarily dating to the Late Byzantine and Early Islamic periods. In addition, there were 10 baskets of glass production waste, probably dated to the Late Roman and Byzantine periods. Area 30 was outside the southern wall of the castle, on the southern ramparts. An Abbasid dated floor of lime mixed with shell was uncovered above the rampart and stepped foundations from the earlier castle building phase. 124 baskets of glass were collected, including 20 baskets of production debris most likely dumped from a nearby workshop. Dating from Ha-Bonim was very good. Two samples are early 8th century (Fig. 5.4f), two from the late 8th century (Figs. 5.5c, d), ten to the 9th-10th century (Figs. 5.6e. g), four to the 10th-11th century (Figs. 5.7c, d) and a final four vessels are dated from the 9th to early 11th and were split evenly over both date categories. Types are domestic, mainly bottles and bowls. Decoration was predominately mould blown, with one tonged and one trailed vessel. Colours are varied, with natural green, blue and brown vessels, but colourless was the most frequent.

5.2.3.6 Jerusalem

Glass was sampled from two excavated sites in Jerusalem. The first is the City of David Spur at the site of the Giv'ati car park, excavation Permit A-3835. The location of this site is just to the south of the modern day city walls, and was a residential area during the Early Islamic period. The site report is pre-publication, however Islamic period

residential stone buildings with beaten earth floors and water cisterns overlaying two phases of Byzantine period structures are reported from an adjacent site, Permit A-3834 (Shukron and Reich 2005). Additional excavations have been performed overlaying the same and adjacent areas and these are published by Ben Ami (2013). He reported residential occupation from the 9th-10th century and possible abandonment in the 10th century (Ben Ami 2013, 3). The finds of Early Islamic glass at also published (Gutreich 2013; see Chapter 2). A second excavation published by Ben Ami (2008) of excavations from March-Oct 2007 (Permit A-5071) was in the North-West corner of this site and identified one Umayyad phase, and four Abbasid phases, indicating dwellings of a residential district occupied until the final phase. Other excavations of this area are published by Macalister and Duncan (1926); Crowfoot and Fitzgerald (1929) and Kenyon (1974). The glass from this site is described in Winter (forthcoming B). Fifteen samples were chosen from this site for analysis dating from the late 6th century until the 11th (Late Byzantine - Fatimid); this included 4 late 6th-early 8th century samples which were classified into the 7th century date category (Figs. 5.3b, c); 2 samples as early-mid Abbasid and were put into the late 8th century date group (Fig. 5.5b), although could continue into the 9th century; 3 samples dated 9th-10th (Fig. 5.6i) and 2 samples dated 10th-11th century (Fig. 5.7e). The vessels consist of typical domestic wares – lamps, bottles, bowls, beakers. Colouration was mostly pale blue to greenish blue and a few colourless. One was cobalt blue, an elongated bottle (JER 3835-07) similar to vessels sampled from Ramla (e.g. RAM 4768-08; RAM 6297-05). Decorative techniques included one each of applied trail, tonged, mould blown and relief cut types. Note that four samples (JER 3835-12, -13, -14, and -15) – two window panes, a stirring rod and a beaker – are missing their dating and although analysed will not be included in the discussion.

The second excavation was in the Old City, the site of the Wilson's Arch and Great Causeway, which also encompasses an area known as the Western Wall Tunnels, Permit A-5124. This area was just to the West of the Temple Mount and was developed as a Muslim area during the Early Islamic period (see Chapter 2). This location has undergone numerous excavations over the years (see references in Onn et al 2011). Weksler-Bdolah et al (2009) in the 2005-2009 excavations of the Western

Wall Plaza, adjacent to this site, found 8th-9th century occupied buildings which became neglected in the 10th century. The Wilson's Arch excavation (Permit A-5124; May 2007-April 2010) is partially published by Onn et al (2011) and describes some of the glass-containing contexts. The excavations uncovered vaulted rooms and buildings beneath the causeway, mostly from the late Roman period. The Great Causeway itself and the

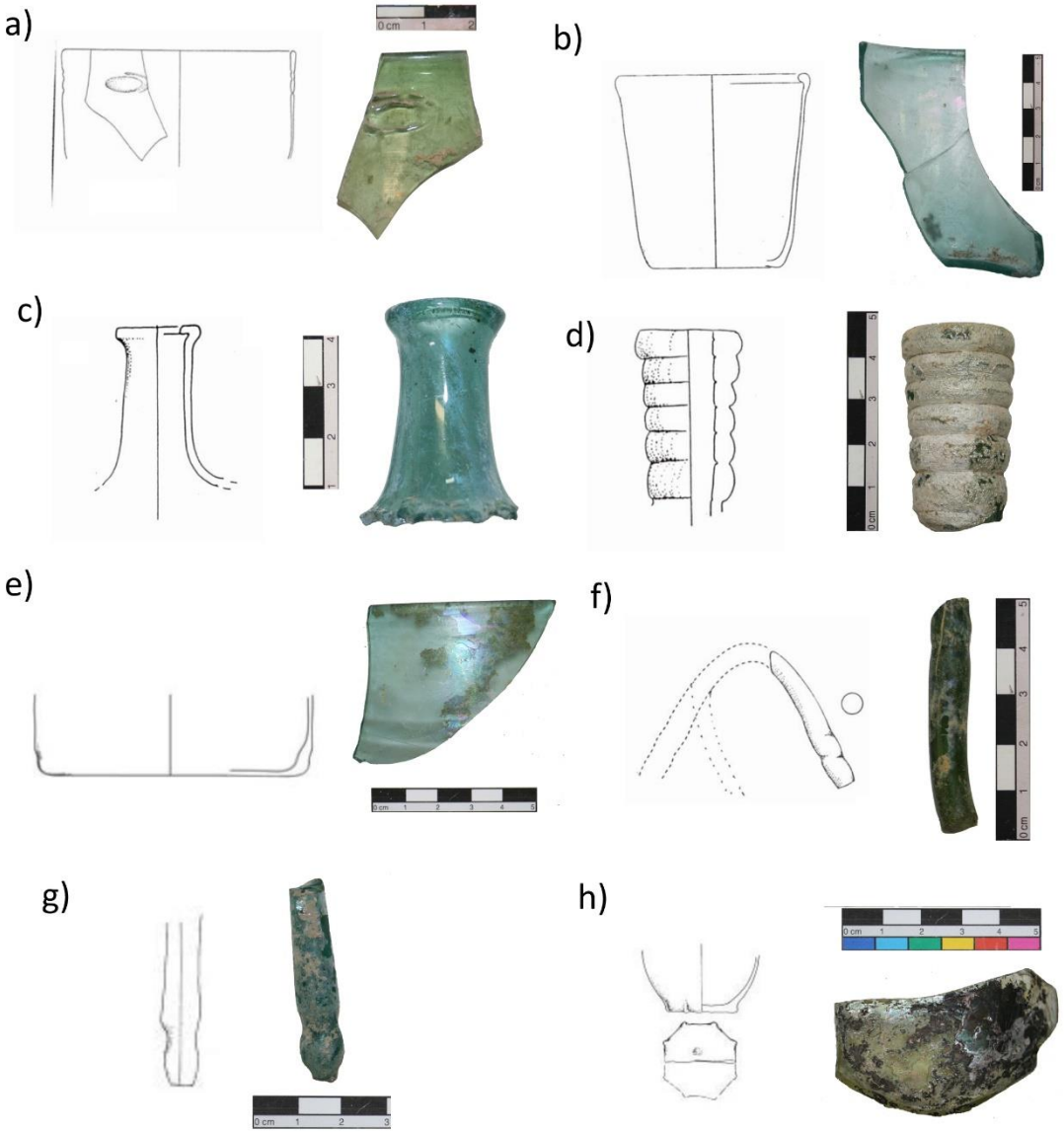


Figure 5.5. Examples of vessels dated to the Early Abbasid period, mid-8th – early 9th century. a) AY 2989-01; b) JER 3835-05; c) HB 3032-03; d) HB 3032-04; e) RAM 4768-02; f) RAM 3592-02; g) RAM 4740-01; h) RAM 4740-05

Secret Passageway were also built at this time, but the site saw little actively during the Byzantine period. In the Umayyad era the top of the Secret Passageway was covered with a barrel vault and a staircase was built linking the Passageway to the Street of the Chains above. The site was occupied in the Abbasid period but no significant building activity took place. The samples came from permits A-5124-2007 and A-5570-2009, amounting to a total of 31 samples of glass, described in Katsnelson (forthcoming B).

Overall, the glass dates from Umayyad to Fatimid periods, with the vast majority being late 7th-early 8th century types: 21 samples were put into the 7th century date bracket although some of these probably continue into the early 8th century (Figs. 5.3g, I, j). Five more samples from separate contexts were placed into the early 8th century dating group, this later date was based on changes in fabric quality and colour, indicating differences to previous vessels (Figs. 5.4d, e). Three samples dated to the 9th-10th century (Fig. 5.6l), with another dating to the 9th-early 11th and is split over both date groups. These samples came from a number of site locations, including a number from Building H (the Secret Passage) and an area of new stairway built during the Umayyad period. Samples came also from room 31 in Building B, an area that became used as a refuse pit during the Abbasid period (9th-10th century). The forms are mainly domestic – bottles, a number of oil lamps, wineglass and jug. A few rarer and more specialist items included an alembic (JER 5124-08) and a trick bottle (JER 5124-04; Fig. 5.3i). The glass colours were principally greenish blue. It is noted that Umayyad glass working debris was also present at this site.

5.2.3.7 Nahal Shoval

Nahal Shoval (Nahal Stream) is a rural settlement located in the Negev near Beersheva. The site was excavated by Nir-Shimshon Paran (Permit A-6362). 350 glass fragments and one raw glass chunk were uncovered from Areas I and L dating from the late Roman to Abbasid period, reported by Winter (forthcoming C). This glass came from an area of settlement founded around the late 5th/early 6th century, abandoned sometime in the 9th century and then reoccupied during the Mamluk period. Previous nearby excavations have found Early Islamic period buildings (Daniel 2005). Ten samples were

chosen for analysis, these included bowls, beakers and bottles. Decorated items comprised a stirring rod with trailed decoration, a bottle with a thick wavy trail and tonged bowls. Colours were mainly greenish blue but also included later dated colourless vessels. The date ranged from the Umayyad 8th to Abbasid-Fatimid 11th century. Five samples were dated to the early 8th century (Figs. 5.4h, i), four to the mid-Abbasid 9th-10th century (Fig. 5.6h), and one vessel from the 9th-early 11th split over the 9th-10th and 10th-early 11th dating categories.

5.2.3.8 Ramla

A total of 97 samples were taken from seven excavated sites around Ramla, a city founded around c. 715. Consequently, the glass recovered from Ramla have a *terminus post quem* of 715 CE, which provides a convenient separator between glass from the 7th and that from the 8th centuries.

The samples taken from the excavation under Permit A-3592 were supervised by A. Nagorski but have not yet been published. Six samples were chosen dating from the 7th to 11th century and are described in Gorin-Rosen (forthcoming B). One vessel (RAM 3592-01; Fig. 5.3f) was context-dated to the early 8th century but was a Byzantine wineglass with beaded stem typical of the 7th century and therefore dated to this period. One vessel dated to the late 8th (Fig. 5.5f) and the remainder to the 9-early 11th, being split over both date groups. Forms included mould blown and wheel cut bottles, as well as a horseshoe-shaped object (RAM-3592-02) and a small shoe-shaped cobalt-blue bottle (RAM-3592-03). The vessel fabrics are mainly greenish to colourless.

The samples from Permit A-3897 was excavated by O. Shmueli (Shmueli 2012; 2016) from Danny Mass Street. This site was located on the north eastern fringe of the present day, old city, 450m east of the White Mosque. Five strata were exposed, the prime one containing a residential building in use from the 9th-11th centuries, where a wide range of pottery vessels were reported, including imported types. Eight vessel fragments were selected for analysis, all of which dated to the Abbasid-Fatimid period (10th-early 11th century; Katsnelson 2016; Figs. 5.7f, g). There were a mix of vessels, including a cylindrical beaker (RAM 3897-07) and lamp with wick tube (RAM 3897-03),

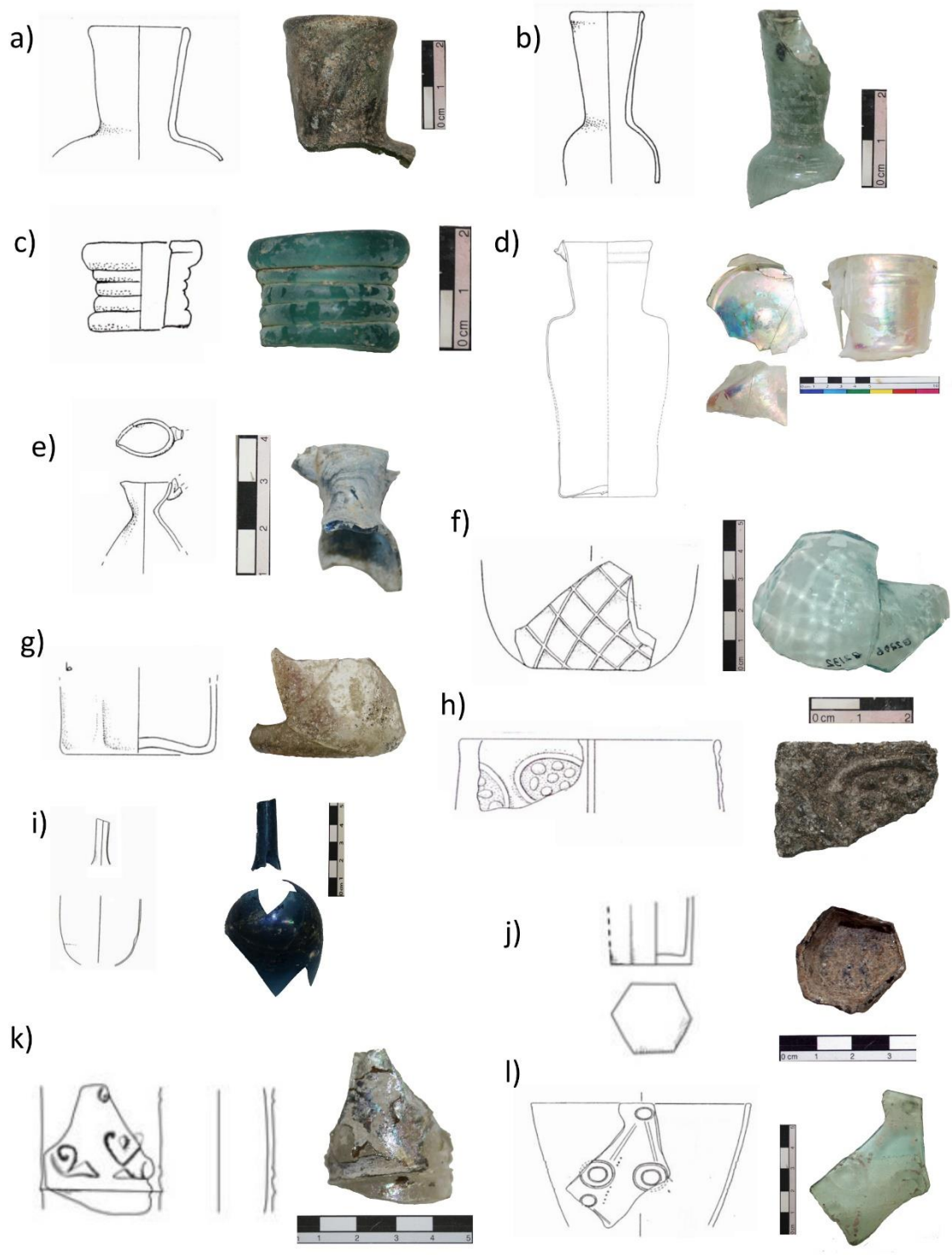


Figure 5.6. Examples of vessels dated to the mid-Abbasid period, 9th-10th century. a) AY 2844-02; b) AY 2989-03; c) AY 2989-05; d) BSH 2885-02; e) HB 3032-06; f) JER 5124-30; g) HB 3032 07; h) NS 6362-06; i) JER 3835-07; j) RAM 4768-04; k) RAM 4768-05; l) JER 5124-28.

both recognised as Serçe Limanı types. In addition, there was a high quality colourless wheel cut bottle (RAM 3897-04) and a bottle with an engraved Star of David (RAM 3897-08), a similar type has been found from Fustat. These were possibly imported. Most vessels were colourless, except for a cobalt-blue elongated bottle (RAM 3897-05).

Permit A-4740 covered a 2006 salvage excavation at Ma'asiyaha junction published by Haddad (2013) with a glass report by Gorin-Rosen (2013). The excavated site was of an Early Islamic period road bed, with road fill comprising stones mixed with dumped occupation debris – potsherds, bone, bronze and steatite objects – as well as glass fragments. 68 vessel fragments and 4 chunks of raw glass were found. The glassware point to a rich array of types, suggesting they came from a nearby residential district. Some glass working debris suggests that glass working waste was dumped from a workshop identified in nearby Moshav Mazilah. Thirteen samples were taken for analysis. Dating was by form and context covering the late 8th-11th century with a single fragment from a Mamluk fill assigned to the 13th century. One sample (RAM 4740-01; Fig. 5.5g) was linked typologically to the Umayyad-Abbasid period and was consequently dated to the late 8th century, it fell into Locus 112 with two other vessels, which were also tentatively dated to this period based on their association (RAM 4740-05; 07; Fig. 5.5h) – however this dating is not secure and these vessels could belong in the 9th century. Of the remaining vessels, nine dated from the 10th-11th century and one to the 13th century Mamluk period. The forms were a mix of types which included a likely imported wheel-cut and hexagonal facet-cut bottles (RAM 4740-01; -12), a bowl, jar, ampoule and a horseshoe shaped object, as well as a few unidentified types dated by stratigraphy. Colours were mainly pale blue or colourless.

The area of Permit A-4768 was a 2006 salvage excavation on the Lod to Na'an railway track, published by Haddad (2010) and with a glass report by Gorin-Rosen (2010B). Twenty 4x4m squares were excavated, uncovering white plaster floors, walls and installations within buildings. Pottery dated the buildings to the late 8th-10th century Abbasid period. Glass working debris and 74 fragments of glass were excavated dating to the Abbasid-Fatimid periods. Eleven samples were taken for analysis, three of these (RAM 4768-01, -02 and -03; Fig. 5.5e) were early Abbasid types belonging to the late

8th century, while the remaining were typical Abbasid, and allocated to the 9th-10th century dating group (Figs. 5.6j, k). The types were mainly bottles and bowls, although a horn-like object (RAM 4768-06) was a more unusual addition. Two types of glass were discerned (Gorin-Rosen 2010B), one locally produced of generally plain and domestic wares, the other decorated with fine bevelling and cutting, possibly imported, for example a high quality hexagonal bottle (RAM-4768-04). Colours were a combination of greenish-blue for the earlier glass and colourless for the later vessels, as well as two cobalt blue samples – RAM 4768-09 a thimble-like jar and RAM 4768-10 an elongated bottle.

The vessels taken from Permit A-5947 came from a salvage excavation (June 2010) conducted at the Ha-Nevi'im Nursery School on Maimon Street. The excavation, published in Haddad (2011), was approximately 400m north of the White Mosque. Nearby excavations at Permits A-5837 (Korenfeld 2015) and A-6016 (Toueg 2011) found Abbasid and Fatimid period installations and cisterns. Two squares were opened (A1 and A2) revealing crushed chalk floors, fills and refuse pits. Two principal phases were identified, an 8th century phase and a later 9th-10th century phase. One hundred fragments of glass were discovered, of which a selection is described in Gorin-Rosen (2011). Thirty-one samples were taken for analysis, the majority of the vessels, 24 in total, dated to the beginning of the settlement in the Umayyad early 8th century (Figs. 5.4g, j), mainly of material from Locus 112, a fill in square A1, and Locus 114 from A2. This material was predominately greenish-blue in colouration and consisted of bottles, jars, bowls, cups and lamps, with occasional mould blown and pinched decoration. The remaining samples dated by form and context to the 9th-12th centuries with one vessels of late 8th-9th century date, three from the 9th-10th century, two of the 10th-11th century, and a final sample dating to the 11th-12th century (Fig. 5.8d). These vessels came from fills of Abbasid-Fatimid period rubbish pits (e.g. L102; L109) and were primarily colourless. Forms included a bowl, cup, jug but also two wheel-cut bottles (RAM 5947-29 and 31).

Permit A-6297 was a 2011 salvage excavation at the corner of Ha-Etzel and Ha-Gedud Ha-Ivri Street excavated by R. Toueg (Toueg 2013). A number of buildings were excavated from this site. They dated to the Abbasid-Fatimid period, mid 8th-10th

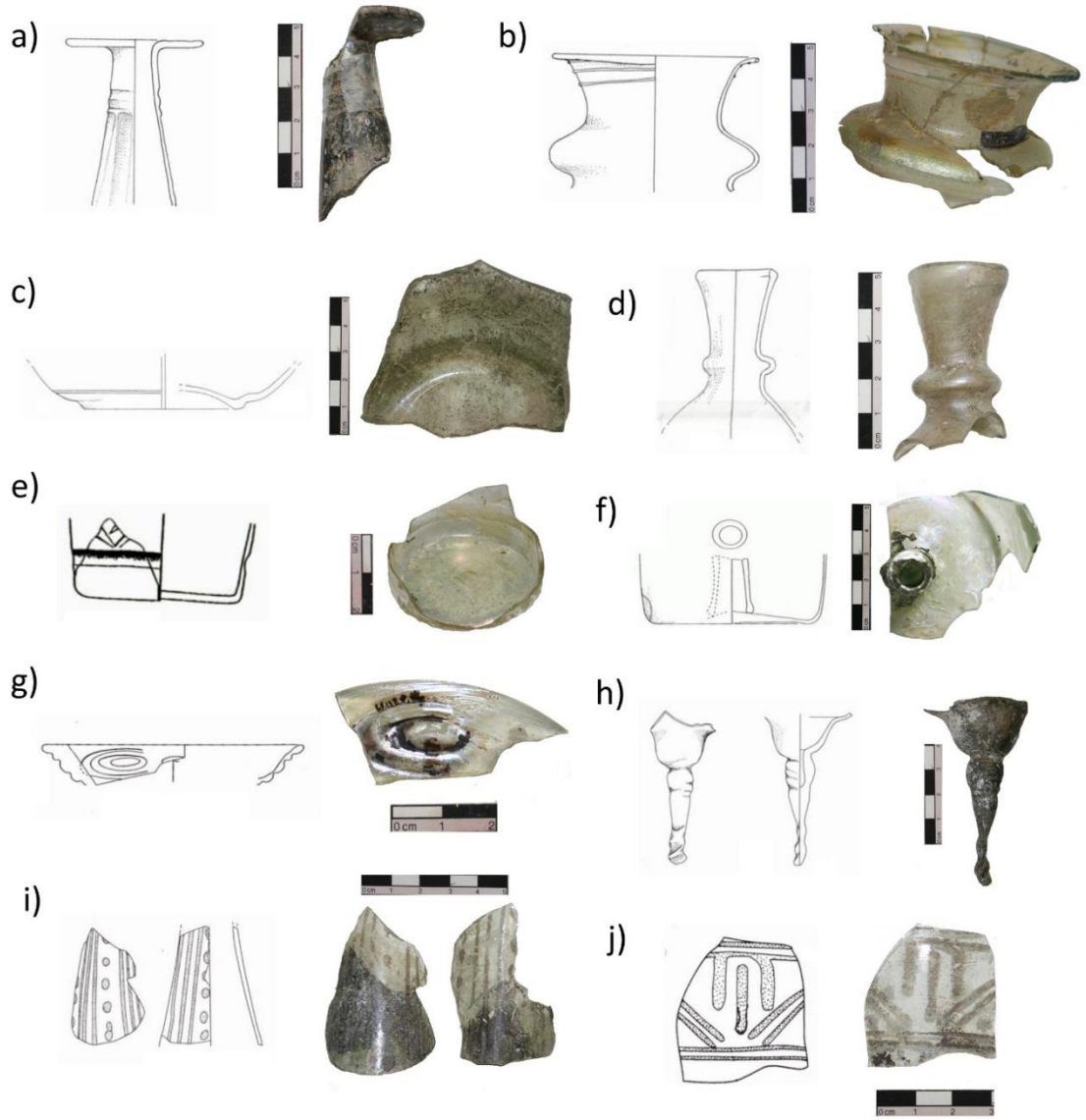


Figure 5.7. Examples of vessels dated to the Abbasid-Fatimid period, 10th-early 11th century. a) AY 2989-14; b) AY 2844-06; c) HB 3032-21; d) HB 3032-32; e) JER 3835-11; f) RAM 3897-03; g) RAM 3897-06; h) TIB 5583-30; i) TIB 5583-27; j) TIB 5583-29

century, but abandoned soon afterwards. Nearby excavations found further buildings and installations from the Abbasid, Fatimid and Mamluk periods at Permit A-2347 (Glick and Gamil 1999) and B-207/2000 (Toueg 2006). Nineteen squares in two areas were excavated identifying four strata from the Abbasid to Modern Period containing five buildings with three Abbasid to Fatimid period construction phases. Glass was found in the pit fills. Winter (2013) describes the 160 excavated fragments as of *'rich typological variety'* although most vessels were common types. Sixteen samples were

chosen, which included small bowls, bottles, as well as large plates similar to Serçe Limanı types. Nine samples were identified to the late 8th to 10th century and were put into the 9th-10th date group, while the remaining 8 samples dated to the Abbasid-Fatimid 10th-11th century and have parallels on the Serçe Limanı wreck. One rarer item was an inkwell (RAM 6297-08), a high-status item found in Building 1, dating 9-10th century. Elongated cobalt blue bottles were the only coloured types, amongst the more common greenish to colourless glass. Decorations included incised and mould blown types.

Permit A-6490 was an excavation on Ha-Hez Street conducted in May 2012 (Toueg and Torgë 2015). Nearby excavations are published in Sion (2000B; 2009), Elisha (2010), Torgë (2011; 2014) and Toueg and Arnon (2011) which found buildings and installations from the 8th to 11th century. Ten squares were excavated revealing a street intersection, an alley and the remains of four buildings covering two strata, the first was Abbasid mid-8th-10th and second, Fatimid 10th to 11th in date. Eighty glass fragments were uncovered as reported by Winter (2015). Twelve samples were chosen for analysis. A variety of objects were selected, emanating mainly from room fills (e.g. L131, L138) and street fills (L141, L142; see Toueg and Torgë 2015). Dating was primarily to the 9th-10th century, although three vessels dated earlier to the Umayyad period (early-mid 8th) and one to the mid-late 8th (RAM 6490-04), and a further two samples to the 9th-early 11th and split over across both date groups. Types include bottles, a beaker, a footed bowl (RAM 6490-01) and two horse-shoe shaped objects (RAM 6490-02 and -03). Colours were greenish-blue to colourless, with the colourless vessels tending to date later, plus three cobalt blue vessels, two of which are elongated bottles (RAM 6490-07 and -08). The only decorated samples were two mould blown, one of which was a square cross-sectioned bottle (RAM 6490-11).

5.2.3.9 Sepphoris

Permits A-3791 and A-3821 covered 2002-3 excavations at Sepphoris directed by Y. Tepper (Tepper 2010). Previous work regarding neighbouring areas was published by Porat (2009) and Oshri (2005). Four excavation areas (A-D) were opened along a road

Figure 5.8. Examples of vessels dated to the Fatimid-Crusader period, mid 11th-13th century. a) AY 2989-15; b) BSH 2885-09; c) BSH 2885-11; d) RAM 5947-28; e) BSH 2885-12

at the base of a hill just below the ancient city, where remains of buildings dating to the Late Roman, Byzantine and Early Islamic periods were discovered. The glass finds, published in Gorin-Rosen (2010C), mainly date from the Late Byzantine to start of the Umayyad period (7th century) with only a few Abbasid dating vessels. Sixteen samples were taken for analysis. Ten of these came from Locus 103, which was a habitation layer of an early Umayyad building in Area C built overtop a Byzantine building. Twelve samples are dated to the 7th century Late Byzantine-Umayyad period, and consisted of wine glasses, lamps and bowls (Figs. 5.3d, e, h). Glass working waste was also found from this period, probably dumped from elsewhere, this included raw glass chunks and

bricks with adhering glass. These vessels are mainly pale blue although with some pale greenish-blue examples, one has trailed decoration. The four remaining samples were Abbasid in date, one dated to the early Abbasid period and was assigned a mid-8th-early 9th century date, the final three samples were dated to the 9th-10th century. These vessels are colourless and greenish-blue, and consisted of bottles and bowls, one of which had tonged decoration (SEP 3791-16).

5.2.3.10 Tel Rosh

Tel Rosh was a small settlement within a rich agricultural region bordering the Negev Desert in the south of Israel. No excavation report is yet published. Samples were taken from excavations in Permit A-6055. The glass report was by Winter (forthcoming D) who notes that 20 small glass fragments of types usually typical to Umayyad and Abbasid periods were recovered from a number of rooms. Four vessels were taken for analysis, three bottles and one oil lamp with a hollow stem. Two samples are from the Umayyad period and have been dated to the 7th century. The remaining samples were dated to the early Abbasid period, mid-8th to early 9th century.

5.2.3.11 Tiberias

The samples from Tiberias were uncovered during the 2009 excavation (Permit A-5583) at the Roman Theatre, preliminarily published by Atrash (2010). The Theatre dates to the early Roman period. Islamic glass was excavated from Strata I and II dating to the Abbasid and Fatimid periods. These were within a residential quarter of ten large dwellings separated by streets and alleys that had been constructed within the theatre confines after the 749 CE earthquake. Thirty samples were taken for analysis dating mainly to the Abbasid period but also with some also typologically earlier samples (Gorin-Rosen forthcoming C). Three samples dated to the Late Byzantine/Umayyad 7th century; two (tonged and pinch decorated) to the Umayyad 8th century; one, a scratch decorated blue bowl (TIB 5583-06), dated to the Early Abbasid mid-8th-9th century; an elongated blue bottle (TIB 5583-07) dated to the 9th-10th century; and six samples to the 10th-11th century, these were primarily Serçe Limanı

types (Figs. 5.7h, I, j). The remaining 16 samples dated to the 9th-early 11th century, some of these were similarly Serçe Limanı types. These samples were averaged over the two dating categories. The range of forms are mostly bottles and bowls but included oil lamps, cylindrical beakers and a square sectioned bottle. Colour range from greenish blue to colourless, with two cobalt blue examples and one brown vessel. Most were undecorated, but there were incised, engraved, faceted, tonged and trailed examples.

5.3 Analytical Technique

5.3.1 Introduction

Glass chemical information will be gathered through the use of compositional analysis. Glass is made up of a number of oxides in major, minor and trace concentrations. In the majority of glass studies major and minor oxides are sought using techniques such as scanning electron microscope energy dispersive X-ray spectroscopy (SEM-EDS; e.g. Freestone *et al* 2000; 2002A; Paynter 2006). In more recent years electron probe microanalysis (EPMA) using a wavelength dispersive X-ray spectrometer (WDS) has become popular. This technique has lower detection limits, and is well suited to glass research (Henderson 1999; Henderson *et al* 2004; Schibille et al 2008; Silvestri *et al* 2008; Rehren *et al* 2010). However, while EPMA is an improvement over SEM-EDS in detection limits, it can only provide limited trace oxide information.

For provenance studies, accurate quantification of trace oxides is certainly beneficial and occasionally essential. In previous work successful matches between glass reference groups and samples of unknown origin have been identified using major and minor oxide data (e.g. Freestone et al 2002A; Rehren et al 2010; Rosenow and Rehren 2014; Ceglia et al 2015). However, in certain circumstances, for example when groups of major and minor oxides overlap, a problem often exhibited in Islamic plant ash glass, (see Brill and Stapleton 2012, 421-423) trace oxides can be crucial in defining groups. In addition, the use of only a limited number of oxides may cause superficial or

incorrect groupings to be formed. Therefore, increasing the range of elements to include trace oxides may extend the number of matching values and thereby improve confidence in a match (Wilson and Pollard 2001). Furthermore, some of the trace oxides themselves are particularly useful for provenance, for example oxides from the heavy mineral component of sand do not fractionate relative to one another due to weathering or during glass production. These include the rare earth elements (REE) and elements such as titanium, zirconium, hafnium and lanthanum (Shortland et al 2007). Trace elements are also useful in identifying recycling by looking at colorant element contamination (Jackson 1996; Freestone et al 2002A; Freestone et al 2008B; Jackson and Paynter 2016; Freestone 2015). Such use of trace elements in provenance and recycling is discussed later in Section 5.5.

This project will use laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for the analysis. This technique first had application in geology with the analysis of silicates (Perkins et al 1993; Jarvis and Williams 1993), which led to its archaeological application in the analysis and provenance of archaeological obsidian (e.g. Gratuze 1999) as well as with man-made glass (Gratuze et al 1993). In more recent times it has become more routinely used in glass research (Gratuze and Foy 2012; Jackson and Nicholson 2010; Mirti *et al* 2008; 2009; Wedepohl et al 2011A; Dussubieux et al 2009). LA-ICP-MS has a number of clear and distinct benefits, including extremely low detection limits ranging from 0.01-1ppm depending on the element (Gratuze 1999, 874; Jarvis and Williams 1993, 259). This allows the detection of a wide range of elements, including the REE. In combination with a mass spectrometer incorporating a multi-collector, the speed of analysis is rapid and without need for sample preparation. Finally, an important benefit for use in archaeological research is that the laser creates ablation scars 70-100 µm in diameter (400 µm deep), which are invisible to the naked eye, permitting invasive but non-destructive analysis.

A number of comparative studies of LA-ICP-MS against other methods (SEM-EDS; EPMA; solution ICP-MS) have shown that LA-ICP-MS outperforms the other techniques (see Norman et al 1998; Wagner et al 2008) in terms of its precision and detection limits, leading to LA-ICP-MS becoming the method of choice for accurate and high

precision work (Vicenzi et al 2002; Wagner et al 2012). However, this technique has some limitations; as only minute quantities of analyte is taken, an homogenous material is required for the results to be representative of the whole. Geological glasses (obsidian) are typically homogenous, and while this is generally true for archaeological glass, inclusions or incomplete mixing remain a possibility and this needs to be taken into account.

Fractionation during ablation is another potential source of error. It is produced when ablation creates a bias towards the collection of some elements or compounds over others. This can become more pronounced as the depth of the ablation pit increases. A slight bias towards Ni, Cu, Zn and Pb has been noted when directly compared to solution ICP (Norman et al 1998, 480). Fractionation has been found to be affected by laser wavelength, with definite benefits seen in the use of shorter wavelengths (Guillong et al 2003; Wagner et al 2012), such as the 193nm. This creates smaller particles allowing easier transport and ionisation than longer 266nm wavelengths. Wagner determined wavelength selection most affected the oxides of Al, Ca, Zr, Bi, Sr and K (Wagner et al 2012, 1673-4).

5.3.2 Experimental procedure

Analysis was performed by LA-ICP-MS at the Centre Ernest-Babelon, IRAMAT, at the CRNS facility, Orleans, France, under the supervisor of Dr Bernard Gratuze. There were two campaigns of analysis, the first in July 2013 with 96 samples and the second in February 2015 with 196 samples, making a total of 292. The second campaign used a slightly different analytical arrangement with a new laser system, so the two campaigns will be described separately.

5.3.2.1 Campaign 1

The LA-ICP-MS utilised a VG UV-laser connected to a Thermo Fisher Scientific Element XR mass spectrometer. The mass spectrometer was equipped with a three stage detector containing a dual mode (counting and analog) secondary electron multiplier (SEM) which accommodated a linear dynamic range of over nine orders of magnitude

associated with a single Faraday collector. This setup allows the analysis of major, minor, and trace elements in a single run regardless of their concentrations and their isotopic abundance. This is particularly important as in contrast to solution ICP-MS the dilution of samples is impossible with laser ablation. The ablating beam was generated by a Nd YAG pulsed laser operating at a wavelength of 266 nm and frequency of 7 Hz (5 Hz was used on very thin samples to reduce burn depth), running at 3-4 mJ. The laser was run for 20 seconds of pre-ablation (to burn away possible surface contamination), followed by 50 seconds ablation and collection. An argon stream (1.2 l/min) transports the material to a plasma torch for atomisation and ionisation before quantification in the mass spectrometer. Ablation scars were typically 70-100 µm in diameter and typically 400 µm in depth, but dependant on laser frequency.

The sample feeder contained ten 3 cm chambers, each able to hold around 16 samples depending on size. The samples were secured in place by putty (Figure 5.9). Nine chambers were used for samples and the final chamber utilised for the standards. Samples were positioned on end to present the greatest depth and a fresh fractured edge was selected to avoid dirt and corrosion. Between samples a 1 minute blank was run, and between chambers a longer blank was conducted to flush out the system and measure background element levels. The background count was subtracted from the sample count for each session to remove noise.

Figure 5.9. Example of the samples held within one cell from Campaign 1.

Due to the small spot size, LA-ICP-MS requires a high level of sample homogeneity. This was tested by analysing two sites from each sample. Differences were found to be

<10 relative percent (R%) between sites for most elements. During data collection a live count was observed so that elemental spikes or drop-offs due to inclusions or corrosion could be quickly recognised. If seen, these analyses were either adjusted to remove the problematic collection period or the results were discarded and retaken. A final test of sample homogeneity and to compare the analytical procedure against a more established technique, was to analysis the samples of Campaign 1 with EPMA and compare the results to that of LA-ICP-MS.

EPMA analysis used a WDS detector and was performed at the Wolfson Laboratory at UCL by Kevin Reeves on all the Campaign 1 samples. A total of 24 elements were measured using an average of 7 areas per sample at 800 times magnification. The EPMA was run at a 15 kV accelerating potential. A comparison of the major and minor oxides between the LA-ICP-MS and EPMA proved very favourable with an average R% Difference between the results of <5% in MgO, Al_2O_3, SiO_2, CaO, MnO, Na_2O, Cl, Fe_2O_3 (Table 5.3; see Figures 5.10 and 5.11). The resultant differences between the techniques in these elements appear to suggest random scatter rather than systematic difference, however, the slightly larger negative value for Na_2O (-4.67%) might suggest a systematic under-reporting by LA-ICP-MS (or over reporting by EPMA). Slightly larger differences are seen in P_2O_5 (7.19%), K_2O (6.05%) and TiO_2 (10.57%). For these elements this may well reflect increased inaccuracy in the EPMA at lower abundances due to the lower detection limits of the technique, resulting in underestimation. Increased dispersion at lower concentrations can be seen in Figure 5.11. On the whole, this demonstrates very close similarities between the techniques and signals that that LA-ICP-MS is a reliable technique for major and minor elements quantification with comparable results to EPMA, and better results at lower concentrations.

In terms of the potential heterogeneity within the samples, the similarity between techniques shows that LA-ICP-MS was producing results representative of the bulk composition of the vessels. This confirms that the samples are homogenous and that useful data is being produced. There is only a single sample, AH 3746-06, that demonstrates large scale differences between the techniques, however this was caused by error during sample preparation, meaning proper analysis could not be conducted and so this datum will be ignored. Some others samples demonstrate small

Table 5.3. Inter-comparison of the major and minor oxides using LA-ICP-MS and EPMA of the samples from Campaign 1. Relative percentage (R%) differences demonstrate close correspondence between the two techniques. Values in weight %. N = 92 samples.

	Na_2O	MgO	Al_2O_3	SiO_2	$P2O_5$	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
LA-ICP-MS Mean	13.16	1.73	2.26	70.80	0.17	0.83	1.16	8.65	0.14	0.289	0.65
EPMA Mean	13.80	1.75	2.31	69.62	0.16	0.79	1.24	8.95	0.13	0.293	0.63
Average Difference (LA-ICP-MS - EPMA)	-0.64	-0.02	-0.04	1.18	0.01	0.04	-0.07	-0.30	0.01	-0.005	0.02
Relative % Difference	-4.67	-0.88	-1.90	1.70	7.19	4.46	-6.05	-3.33	10.57	-1.61	3.44
Standard Deviation	0.56	0.08	0.12	0.74	0.02	0.05	0.07	0.41	0.02	0.02	0.07
Coefficient of Variation	4.27	4.64	5.32	1.05	12.03	5.43	5.88	4.77	13.15	6.73	10.48

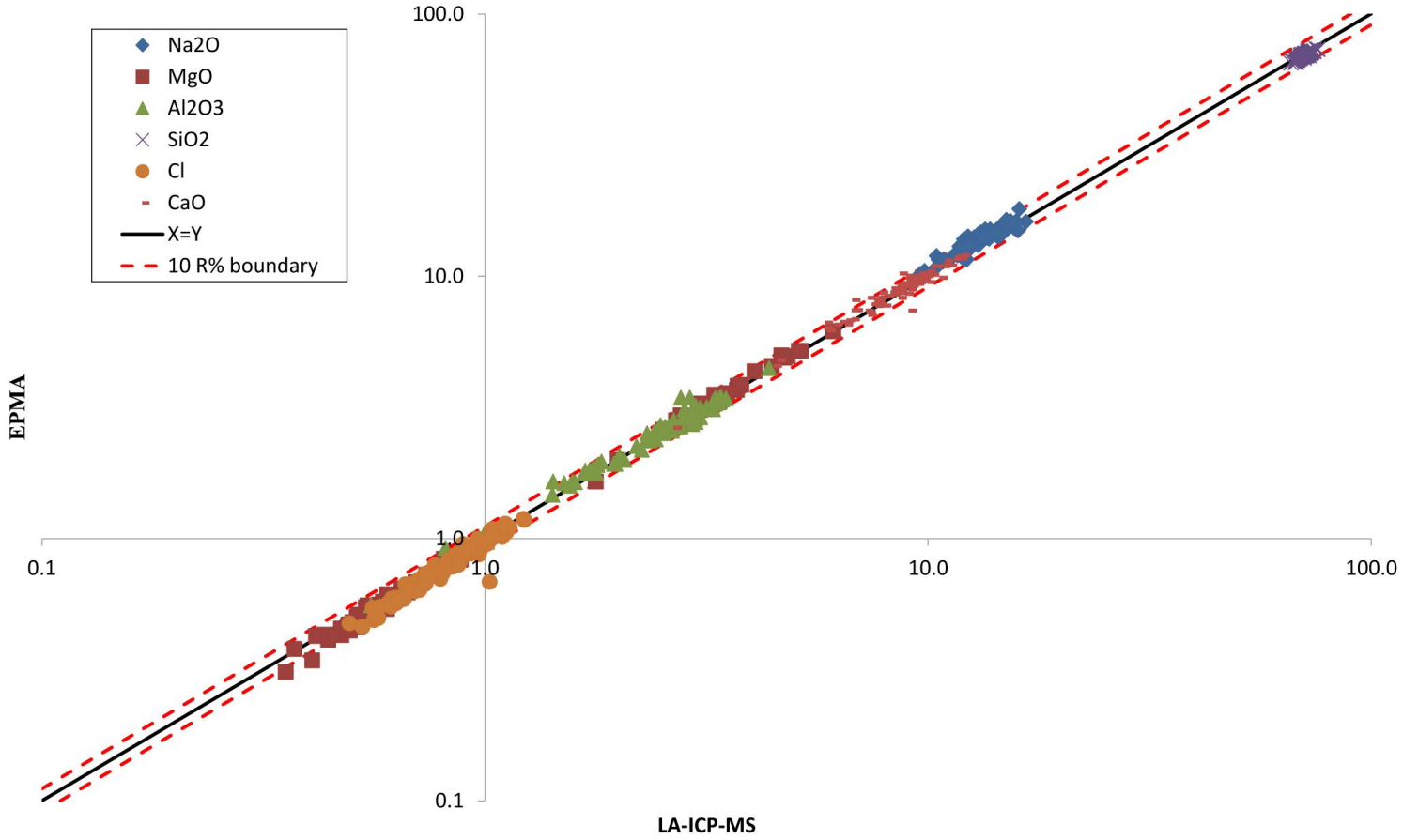


Figure 5.10. Comparison of the major and selected minor oxides analysed by LA-ICP-MS in Campaign 1 and EPMA. Weight %. Log scale. X=Y line and 10% relative % boundaries are marked. Close similarity between the techniques are shown with most oxides within 10%R variation.

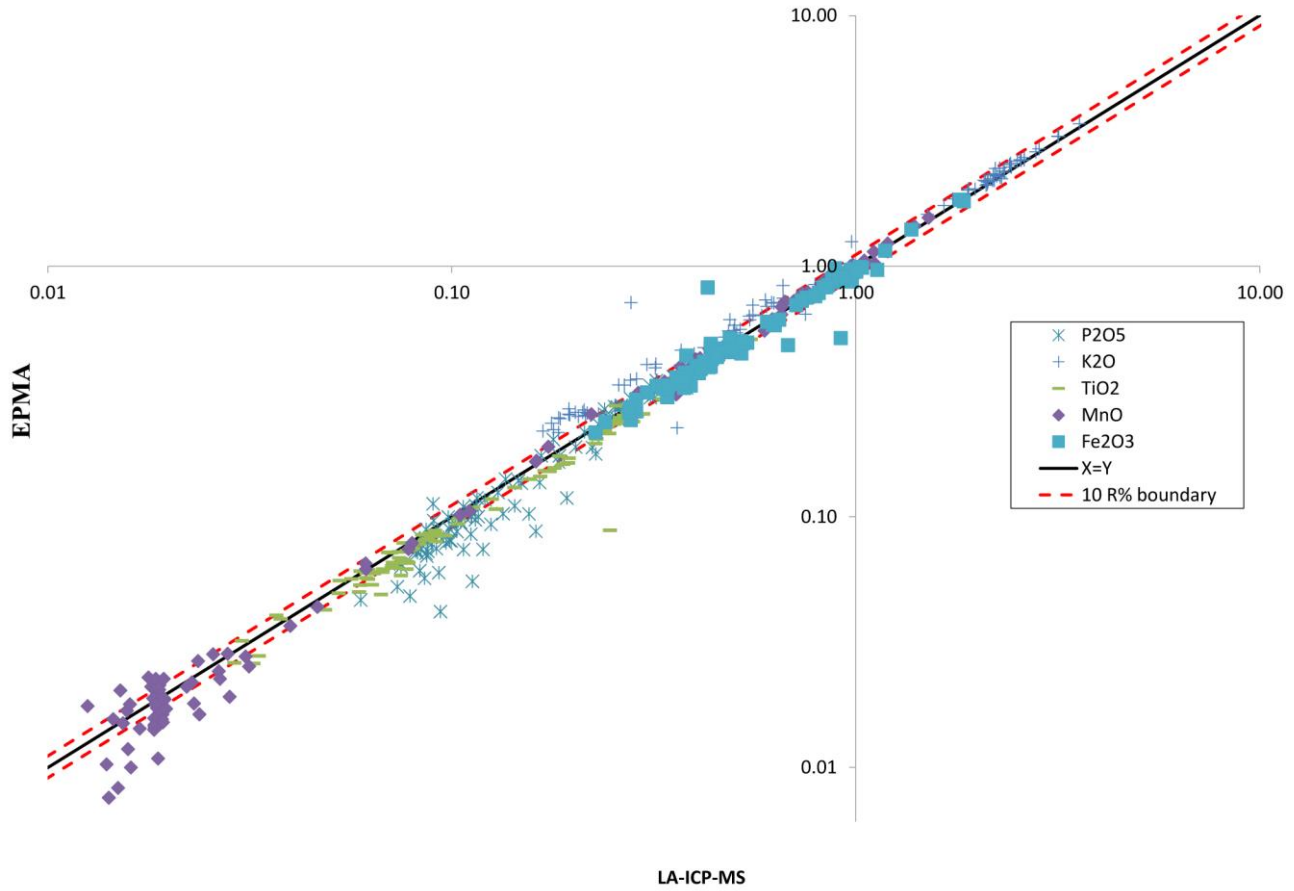


Figure 5.11. Comparison of the minor oxides from LA-ICP-MS of Campaign 1 and EPMA. Weight %. Log scale. X=Y line and 10% relative boundaries marked. Close similarity is mainly shown, although with a slight underestimation of potash by EPMA and overestimation in other oxides of lower abundances, probably linked to lower detection limits of the EPMA technique.

scale differences in one or two oxides; for example, AH 3746-13 shows a difference of -20 R% CaO and -18 R% Al_2O_3; SEP 3791-08 and -15 indicates differences of -18 R% and 6.6 R% in CaO and Fe_2O_3 respectively; RAM 5947-14 showed a difference -28 R% in Fe_2O_3. These are exceptions and for most samples a very close correlation is seen between both techniques.

This comparison demonstrates that LA-ICP-MS is suitable for major and minor oxide analysis with results comparable or better than that produced by EPMA, and that the samples are homogeneous with the LA-ICP-MS results representative of the bulk sample. The EPMA data is provided in full in Appendix E.

5.2.3.2 Campaign 2

An equipment upgrade during the winter of 2014 meant that the analysis in February 2015 benefited from a new laser and gas collection system. The mass spectrometer remained unchanged but the new ablation device was a RESOnetic Resolution M50e. This was an excimer laser produced by argon fluoride at 193nm wavelength. Power was set to 4 mJ and 7 Hz pulse rate. This system used a dual gas collection with helium released at the base of the chamber carrying the ablated material to an argon stream that transported the material to the plasma torch. Use of helium has been proved to significantly increase analyte signal intensities (Eggins et al 1998, 286). Helium flow rate was 0.6 l/min and argon at 1.2 l/min. Ablation was set for 1min 10 seconds, with 50 seconds collection time. Spot size was set to 100µm for most samples, and was only reduced when saturation occurred (reduction to 70µm at lowest). The main causes of saturation were elements with only one usable isotope, e.g. Mn, Cu, Al and Mg.

A single sample tray was used, which could hold up to 100 small 1-5mm samples along with reference standards (Figure 5.12). Blanks were run between every 15-20 samples. During Campaign 2 only one analysis was performed per sample. The high precision of the system and the homogeneity of the samples as demonstrated from Campaign 1 allowed this to be considered acceptable. Nonetheless, methods were employed to check for heterogeneity; live counts were observed during analysis to monitor drop-offs, element spikes or saturation and if evident those results were discarded and the

sample re-run. Additionally, after the data was processed, any results considered unusual were flagged and the analysis re-run. Repeats were performed on two sample (TIB 5583-01; JER 5124-09) due to their slightly unusual composition, but near identical analyses were produced in each case. Two samples (RAM 6490-07 and -08) were repeated as they had reduced amounts of trace elements, this was found to be due to saturation of the beam and the inaccurate reading was discarded. A further five samples (TIB 5583-16; NS 6362-01; -05; HB 3032-18; JER 5124-22) were analysed twice to test agreement between analyses. Very close agreement is seen in major and minor oxides with average relative variation <3% for all except P_2O_5. Some larger differences were seen in certain oxides in individual results, such as P_2O_5 in JER 5124-22. For the trace elements, most showed <10% relative difference, exceptions at 10-20% included PbO, WO, Tm_2O_3, SnO_2, In and ZnO. A further 11 elements had larger variations. The data for these comparisons are shown in Appendix F.

Figure 5.12. Tray of samples for analysis as part of Campaign 2. Standards are at the top and right.

5.3.3 Calibration

For both campaigns the same calibration and quantification methods were used. The full details of the quantification methods are published in Gratuze (1999), so will only be discussed briefly here. Calibration was performed using five reference standards; NIST610, Corning B, C and D, and APL1 (in-house standard with a few specific elements – Cl, Na, Mg, Al, P, K, Ca, Mn, Fe – determined using Fast NAA; for more details on standards see Gratuze 2013). After a 2-3 hour warm up period all the standards were run and then run periodically throughout the session (Campaign 1 every 2 chambers; Campaign 2 every 20-30 analyses) to correct for drift. The standards were used to calculate the response coefficient (k) for each element (Gratuze 1999, 873) which allows the counts to be weighted. The calculated values were normalised against ^{29}Si, the internal standard, to produce a final percentage. A correction for isotopic abundances also has to be performed. Details of calculations used to produce the results are given by Gratuze (2013; 2016, 183). Corning A and NIST612 were analysed independently of calibration to provide comparative data. During the running of blanks the background levels were measured and this was subtracted from the raw counts which increased detection limits by the removal of noise. The end results are reported as element ppm, which are then converted to percentages and oxides as required. A total of 58 of elements were recorded.

5.3.4 Precision and Accuracy

Accuracy is a measure of the 'trueness' of a result – how close the result is to the true value –, while precision is the difference between multiple readings of the same value (AMC Technical Brief 2003). To assess the accuracy and precision of the LA-ICP-MS, analyses of Corning A (Campaign 1 and 2) and NIST612 (Campaign 2 only) were compared to given values. For Corning A, given values were mainly provided from Brill (1999B) but selected minor and trace oxides were taken from Wagner et al (2012) and additional trace oxide values by Vicenzi et al (2002). Values for NIST612 were taken from Pearce et al (1997). Results for accuracy (relative % difference) and precision (coefficient of variation) are presented in Tables 5.4, 5.5 and 5.6. Additionally, graphs

Table 5.4. Values of Corning A taken by LA-ICP-MS during Campaign 1 compared against known values.

Corning A	Major elements as wt %										Minor and Trace element oxides as PPM							
	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	MnO	Fe_2O_3	Sb_2O_3	CuO	Li_2O	B_2O_3	P_2O_5	Cl	TiO_2	V_2O_5	Cr_2O_3	CoO
Start	13.61	2.45	0.91	68.15	2.80	4.91	1.00	1.12	1.69	1.19	77	1776	1182	1256	7315	59	28	1665
Mid	14.43	2.50	0.93	66.68	2.87	5.08	1.02	1.16	1.81	1.24	111	1826	1188	1338	7543	62	30	1778
End	13.79	2.50	0.95	67.69	2.73	5.06	1.00	1.13	1.75	1.20	95	1767	1200	1323	7440	59	29	1707
Average	**13.94**	**2.48**	**0.93**	**67.50**	**2.80**	**5.02**	**1.01**	**1.14**	**1.75**	**1.21**	**94**	**1790**	**1190**	**1305**	**7433**	**60**	**29**	**1717**
Given Value*	**13.40**	**2.50**	1.00	**67.80**	2.87	5.03	1.00	1.09	1.75	1.17	100	2000	1300	1000	7900	60	**30**	1700
difference from given	*0.54*	*-0.02*	*-0.07*	*-0.30*	*-0.07*	*-0.01*	*0.01*	*0.05*	*0.00*	*0.04*	*-5.64*	*-210.37*	*-110.01*	*305.44*	*-467.35*	*0.09*	*-1.07*	*16.75*
R% difference from given	**4.05**	**-0.73**	**-7.34**	**-0.44**	**-2.48**	**-0.23**	**0.65**	**4.36**	**0.18**	**3.19**	**-5.64**	**-10.52**	**-8.46**	**30.54**	**-5.92**	**0.16**	**-3.58**	**0.99**
Standard deviation	*0.43*	*0.02*	*0.02*	*0.75*	*0.07*	*0.09*	*0.01*	*0.02*	*0.06*	*0.03*	*16.80*	*31.71*	*9.03*	*43.85*	*113.82*	*2.00*	*1.06*	*56.88*
Coefficient of variation	***3.09***	***1.00***	***2.03***	***1.12***	***2.43***	***1.82***	***1.47***	***1.84***	***3.50***	***2.41***	***17.81***	***1.77***	***0.76***	***3.36***	***1.53***	***3.32***	***3.65***	***3.31***

Corning A	Minor and Trace element oxides as PPM continued																	
	NiO	ZnO	Rb_2O	SrO	ZrO_2	Nb_2O_3	Ag	SnO_2	Cs_2O	BaO	CeO_2	Eu_2O_3	HfO_2	Ta_2O_3	PbO	Bi	ThO_2	UO_2
Start	221	527	90	996	47	0.63	16	1564	0.29	4120	0.30	0.02	1.03	0.11	685	9	0.33	0.20
Mid	234	510	102	1049	51	0.66	16	1730	0.39	4455	0.31	0.01	1.08	0.11	766	9	0.34	0.23
End	224	490	95	1024	51	0.62	15	1637	0.29	4240	0.29	0.03	1.04	0.12	704	8	0.34	0.24
Average	**226**	**509**	**96**	**1023**	**49**	**0.64**	**16**	**1643**	**0.32**	**4272**	**0.30**	**0.02**	**1.05**	**0.11**	**718**	**9**	**0.34**	**0.22**
Given Value*	**230**	**480**	100	**1060**	50	0.6	20	**1700**	0.27	**4600**	0.29	0.013	1.12	0.14	**730**	10	0.33	0.21
difference from given	*-3.62*	*28.80*	*-4.01*	*-37.28*	*-0.62*	*0.04*	*-4.18*	*-56.51*	*0.05*	*-328.49*	*0.01*	*0.01*	*-0.07*	*-0.03*	*-11.98*	*-1.21*	*0.01*	*0.01*
R% difference from given	**-1.57**	**6.00**	**-4.01**	**-3.52**	**-1.24**	**6.22**	**-20.89**	**-3.32**	**19.40**	**-7.14**	**4.43**	**44.53**	**-6.20**	**-21.10**	**-1.64**	**-12.08**	**2.51**	**6.27**
Standard deviation	*7.01*	*18.70*	*6.03*	*26.26*	*2.35*	*0.02*	*0.51*	*82.90*	*0.06*	*169.86*	*0.01*	*0.01*	*0.03*	*0.01*	*42.40*	*0.52*	*0.00*	*0.02*
Coefficient of variation	***3.10***	***3.68***	***6.28***	***2.57***	***4.75***	***2.66***	***3.20***	***5.04***	***17.14***	***3.98***	***3.48***	***44.44***	***2.84***	***5.35***	***5.91***	***5.93***	***1.40***	***7.85***

* Given value = Brill 1999; bold is Wagner et al 2012; underlined is Vicenzi et al 2002 Each result is an average of two areas of analysis

Table 5.5. Values of Corning A taken by LA-ICP-MS during Campaign 2 compared against known values.

Corning A	Major elements as wt %									Minor and trace elements as PPM							
	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	MnO	Fe_2O_3	Sb_2O_3	CuO	Li_2O	B_2O_3	P_2O_5	Cl	TiO_2	V_2O_5	Cr_2O_3
Start	13.87	2.54	0.98	66.77	2.79	5.77	1.00	1.10	1.62	1.14	110	2043	1167	1691	7847	66	N/A
Middle	13.63	2.53	0.97	67.19	2.83	5.65	1.02	1.11	1.60	1.14	106	2014	1113	1639	7915	64	33
End	13.94	2.65	0.99	66.30	2.86	5.75	1.07	1.17	1.66	1.22	110	2140	1098	1637	7721	63	31
Average	***13.81***	***2.57***	***0.98***	***66.75***	***2.83***	***5.73***	***1.03***	***1.13***	***1.63***	***1.17***	***109***	***2066***	***1126***	***1656***	***7827***	***64***	***32***
Given value *	***13.40***	***2.50***	1.00	66.60	2.87	5.03	1.00	1.09	1.58	1.17	**110**	2000	1300	1000	7900	60	**30**
difference from given	*0.41*	*0.07*	*-0.02*	*0.15*	*-0.04*	*0.70*	*0.03*	*0.04*	*0.05*	*0.00*	*-1.27*	*65.62*	*-173.99*	*655.67*	*-72.76*	*4.41*	*1.78*
R% difference from given	**3.09**	**2.91**	**-2.15**	**0.23**	**-1.53**	**13.83**	**2.94**	**3.64**	**3.02**	**-0.16**	**-1.16**	**3.28**	**-13.38**	**65.57**	**-0.92**	**7.34**	**5.94**
Standard deviation	*0.16*	*0.07*	*0.01*	*0.44*	*0.04*	*0.06*	*0.04*	*0.04*	*0.03*	*0.05*	*2.25*	*66.22*	*36.68*	*30.20*	*98.51*	*1.22*	*1.63*
Coefficient of variation	**1.18**	**2.60**	**1.45**	**0.67**	**1.33**	**1.13**	**3.75**	**3.42**	**1.83**	**4.04**	**2.07**	**3.21**	**3.26**	**1.82**	**1.26**	**1.89**	**5.14**

Corning A	Minor and trace elements as PPM															
	CoO	NiO	ZnO	Rb_2O	SrO	ZrO_2	Ag	SnO_2	BaO	Ce O2	HfO_2	Ta_2O_3	PbO	Bi	ThO_2	UO_2
Start	1697	234	550	97	1060	56	15	1708	4619	0.31	1.16	0.13	691	9	0.35	0.21
Middle	1676	224	547	93	1032	54	14	1686	4467	0.31	1.05	0.12	626	8	0.35	0.21
End	1771	239	559	97	1059	52	16	1760	4603	0.28	1.12	0.11	677	9	0.33	0.21
Average	***1715***	***232***	***552***	***96***	***1050***	***54***	***15***	***1718***	***4563***	***0.30***	***1.11***	***0.12***	***665***	***9***	***0.35***	***0.21***
Given value *	1700	**230**	**480**	100	**1060**	50	20	**1700**	**4600**	0.29	1.12	0.14	**730**	10	0.33	0.21
difference from given	*14.67*	*2.46*	*71.84*	*-4.36*	*-9.85*	*3.93*	*-4.95*	*18.02*	*-37.25*	*0.01*	*-0.01*	*-0.02*	*-65.45*	*-1.20*	*0.02*	*0.00*
R% difference from given	**0.86**	**1.07**	**14.97**	**-4.36**	**-0.93**	**7.87**	**-24.73**	**1.06**	**-0.81**	**3.56**	**-0.87**	**-13.96**	**-8.97**	**-11.95**	**5.11**	**1.02**
Standard deviation	*50.25*	*7.96*	*6.36*	*1.93*	*15.59*	*1.64*	*0.57*	*38.07*	*83.63*	*0.01*	*0.05*	*0.01*	*34.55*	*0.48*	*0.01*	*0.00*
Coefficient of variation	**2.93**	**3.43**	**1.15**	**2.02**	**1.48**	**3.04**	**3.81**	**2.22**	**1.83**	**4.98**	**4.85**	**6.57**	**5.20**	**5.44**	**3.42**	**0.60**

*** Given value = Brill 1999; bold is Wagner et al 2012; underlined is Vicenzi et al 2002** **Each result from a single analysis.** **No Cr in first reading due to Argon contamination**

Table 5.6. Values for NIST612 taken by LA-ICP-MS during Campaign 2 compared against known values.

Nist 612	Major elements %				Minor and trace glass elements (ppm) - continued below														
	Na_2O	Al_2O_3	SiO_2	CaO	Li_2O	MgO	P_2O_5	TiO_2	V_2O_5	Cr_2O_3	Mn O	Co O	NiO	CuO	ZnO	GaO	Rb_2O	SrO	Y_2O_3
Start	13.46	2.13	72.28	11.73	90	149	174	68	68	N/A	50	45	48	45	46	45	35	91	49
Mid	13.20	2.07	72.95	11.45	86	148	149	69	67	52	51	44	47	45	45	43	34	89	47
End	13.04	1.99	73.28	11.36	85	145	157	73	68	49	49	42	44	42	46	41	34	90	48
Average	**13.23**	**2.06**	**72.84**	**11.51**	**87**	**147**	**160**	**70**	**68**	**50**	**50**	**44**	**47**	**44**	**46**	**43**	**34**	**90**	**48**
Pearce et al 1997	13.88	2.12	N/A	N/A	89	128	126	80	70	58	50	45	49	46	47	45	35	90	49
difference from given	-0.65	-0.05	N/A	N/A	-2.52	18.62	33.56	-10.11	-2.51	-8.09	0.30	-1.32	-2.33	-2.05	-1.26	-1.51	-0.22	0.06	-0.21
R% difference from given	**-4.69**	**-2.59**	**N/A**	**N/A**	**-2.82**	**14.50**	**26.55**	**-12.60**	**-3.59**	**-13.88**	**0.60**	**-2.95**	**-4.76**	**-4.45**	**-2.67**	**-3.39**	**-0.63**	**0.07**	**-0.43**
Standard deviation	0.21	0.07	N/A	N/A	2.43	2.28	12.50	2.35	0.76	2.38	1.19	1.50	1.98	1.67	0.41	1.59	0.80	1.22	1.02
Coefficient of variation	**1.59**	**3.53**	**N/A**	**N/A**	**2.80**	**1.55**	**7.82**	**3.36**	**1.13**	**4.73**	**2.39**	**3.44**	**4.24**	**3.81**	**0.90**	**3.70**	**2.33**	**1.36**	**2.12**

ZrO_2	Nb_2O_3	MoO	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	HfO_2
52	45	40	44	43	45	42	46	49	46	43	45	44	42	45	41	46	42	42	46	43	44
51	44	38	42	41	42	41	44	48	45	40	42	41	39	41	37	42	39	39	43	40	40
52	46	37	42	39	41	40	47	50	46	40	41	40	37	41	36	41	38	38	42	39	39
52	**45**	**38**	**42**	**41**	**43**	**41**	**46**	**49**	**46**	**41**	**43**	**41**	**40**	**42**	**38**	**43**	**39**	**40**	**44**	**41**	**41**
49	48	43	48	46	44	42	42	47	46	41	43	40	43	41	41	43	43	43	45	43	41
3.20	-2.57	-5.05	-5.72	-4.95	-1.56	-1.30	3.88	1.88	0.11	-0.09	-0.05	1.41	-3.08	1.02	-2.95	-0.63	-3.38	-3.07	-1.89	-2.28	-0.09
6.58	**-5.36**	**-11.71**	**-11.87**	**-10.75**	**-3.52**	**-3.09**	**9.25**	**3.99**	**0.24**	**-0.21**	**-0.12**	**3.54**	**-7.24**	**2.47**	**-7.14**	**-1.44**	**-7.89**	**-7.15**	**-4.16**	**-5.31**	**-0.23**
0.85	0.82	1.25	1.00	1.94	1.70	1.00	1.47	1.20	0.66	1.55	1.90	2.18	2.38	2.49	2.58	2.60	2.36	2.25	1.85	2.53	2.63
1.64	**1.81**	**3.27**	**2.35**	**4.72**	**3.99**	**2.46**	**3.20**	**2.45**	**1.45**	**3.77**	**4.47**	**5.27**	**6.03**	**5.88**	**6.72**	**6.09**	**5.98**	**5.64**	**4.25**	**6.22**	**6.44**

Ta_2O_3	PbO	ThO_2	UO_2
38	40	44	43
34	37	42	40
34	45	43	40
35	**41**	**43**	**41**
45	42	42	42
-9.67	-1.26	0.98	-0.91
-21.47	**-3.00**	**2.30**	**-2.17**
2.57	4.13	1.00	1.75
7.25	**10.15**	**2.31**	**4.25**

No Cr in first reading due to Argon contamination

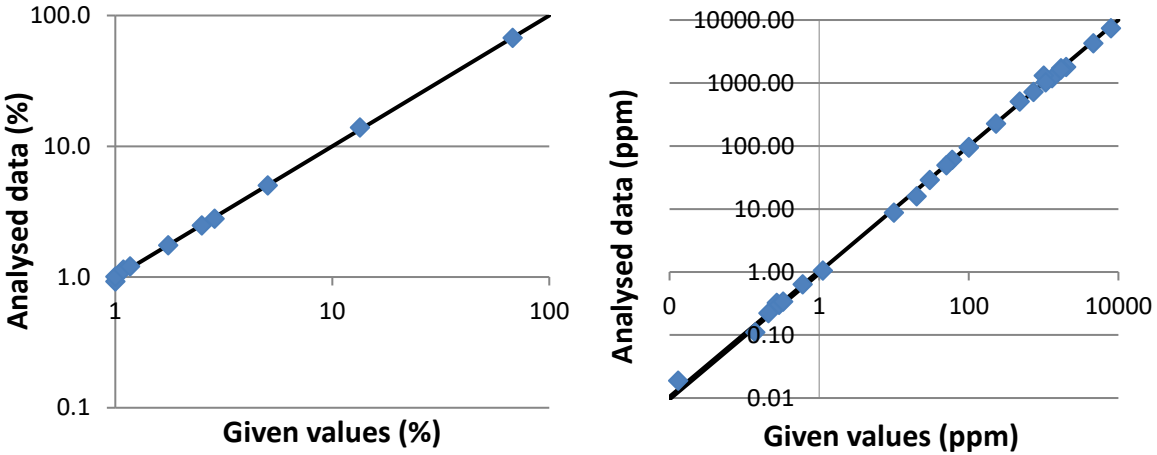


Figure 5.13. Comparisons of Corning A major oxides (left) and minor and trace oxides (right) for Campaign 1. Line is x=y. Both graphs log scale.

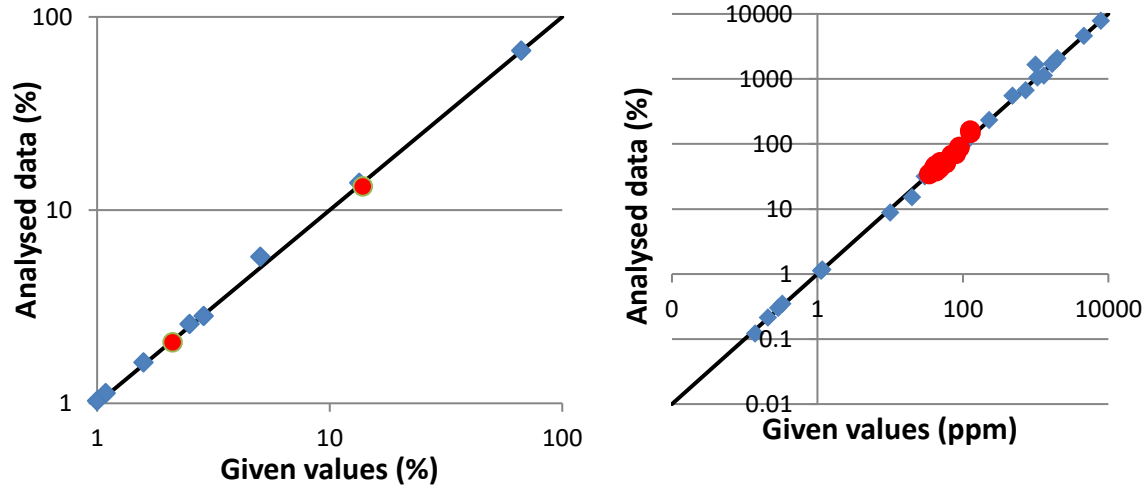


Figure 5.14. Comparisons of Corning A (blue diamonds) and Nist612 (red circle) major oxides (left), and minor and trace oxides (right) for Campaign 2. Line is x=y line. Both graphs log scale.

displaying the measured values against the known values for standards analysed for Campaigns 1 and 2 are given in Figures 5.13 and 5.14. The values for Campaign 1 were averages of two spots, while Campaign 2 from a single spot. Standards were measured at the start, midpoint and conclusion of each Campaign so that potential drift could be investigated.

Both campaigns indicated high accuracy in the analysis. Good correspondence is seen in the major oxides, R% difference was <5% for all oxides with the exception of 7% alumina (Campaign 1) and 13% lime (Campaign 2). Alumina and lime are important oxides in glass chemistry and so to investigate this error further the alumina from samples analysed by LA-ICP-MS was compared against EPMA data, as demonstrated in Figure 5.15. This figure shows very minor variation in the vast majority of samples. As shown from Table 5.3, the combined average difference with EPMA is only 3.67%, with a standard deviation of 0.37. This is better than the 7% indicated from the standard. EPMA analysis was not performed on the samples from Campaign 2, however, glass from a different project was run at the same time, which were also analysed by EPMA, and these can be used to compare the differences between techniques. Comparison of the results for 38 of these samples (CaO data in Appendix G) indicates an average difference of 2.42%, with a standard deviation of 1.69. As demonstrated in Figure 5.16, the results for LA-ICP-MS look to be systematically under-reported against EPMA, although, the disparity is less than 5%. This is less than the 13% indicated from the standards results, and small enough that no correction will be made. These comparisons demonstrate that alumina and lime do not vary significantly from EPMA data and are less than the variation seen against the standards in these oxides. In comparing the minor and trace oxides of the standards, again, high accuracy is evident, with most oxides within 10% of the given value. Deviations between 10-20% are seen in B_2O_3, Cs_2O, Bi for Campaign 1 and in P_2O_5, ZnO, Ta_2O_3, MgO, TiO_2, Cr_2O_3, MoO and Sb_2O_3 for Campaign 2. A number of other oxides have greater differences (Ag, Ta_2O_3, Eu_2O_3, P_2O_3) of up to a maximum of 65% in Cl.

Precision was generally good. All major oxides have coefficient of variation <5%, but with most being <2%. For the minor and trace oxides, most were <5% and all <10% with the exception of Eu_2O_3 at 44% (Campaign 1). Note that Eu_2O_3 is present at

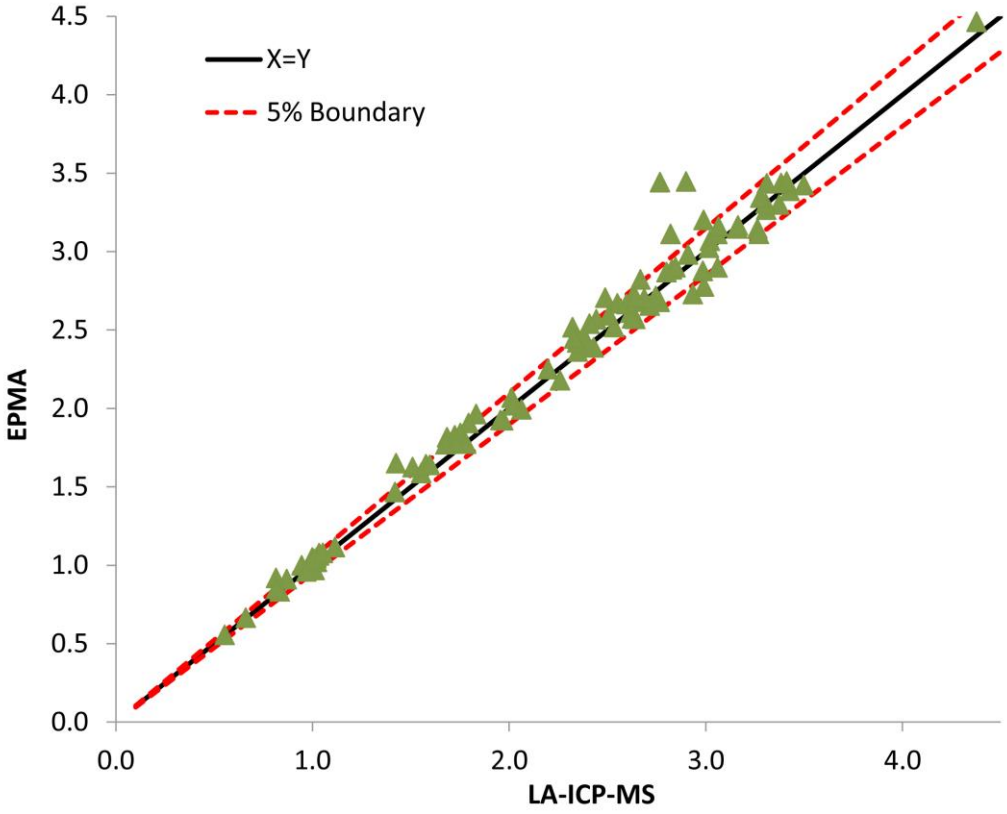


Figure 5.15. EPMA against LA-ICP-MS for alumina from Campaign 1. 5 relative % boundaries marked.

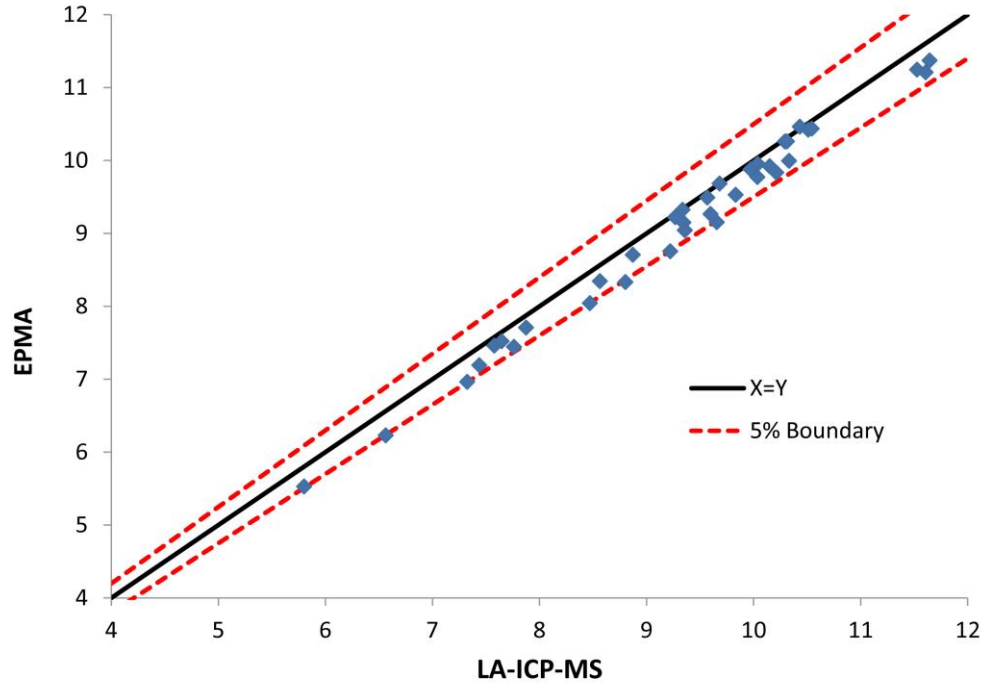


Figure 5.16. EPMA against LA-ICP-MS for lime of glass analysed during Campaign 2. 5 relative % boundary marked.

0.013ppm in Corning A and this extremely low concentration is probably the cause of the inaccuracy, in NIST612 where concentrations are raised closer agreement is evident.

The detection limits of this technique are very low and are dependent, to a certain degree, on the atomic mass of the element. Detection of <10 parts per billion (ppb) is possible with elements such as Pr, Tb, Ho, Tm, Lu, Ta, Th and U, while higher values of 1-10ppm is possible with Li, B, P, Ti, Cr, Mn, Cu, Sn and Ba. A full range of element detection limits for this machine is published by Gratuze (2016, 184), these values will be used in this study.

An analytical problem was encountered regarding the values for chromium during the start of Campaign 2, when one of the argon gas cylinders was found to be contaminated with CO_2, which reacted at the plasma torch to form argon carbide (ArC; mass 52). This has the same atomic mass as chromium (mass 52) and produced a false chromium result. Therefore, chromium data for 49 samples analysed at the start of Campaign 2 was discarded. No problems ensued after the argon cylinder was replaced.

5.3.5 Data Processing and Statistical Analysis

The compositional data facilitates characterisation of the vessels into groups, which in turn can be compared to known composition types in order to provenance glass to production sites or regions. The groupings created in this thesis are determined using multivariate statistical techniques of Hierarchical Cluster Analysis (CA) and Principal Component Analysis (PCA), with further refinement achieved using graphical methods such as bivariate plots. These techniques will aid the process of group characterisation and the visual presentation of results.

Cluster analysis and principal component analysis make an important contribution to archaeological research (for overviews see Baxter 1994; 2001; 2003; Shennan 1997), particularly in the assessment of compositional data for ceramics (see Glascock 1992; Glascock et al 2004; Marengo et al 2005), iron working slag (Charlton et al 2012) and in the characterisation of archaeological glass (Brill and Stapleton 2012; Foy et al 2003A; Picon et al 2008; Silvestri et al 2008; Freestone et al 2002B). Hierarchical cluster

analysis is a way of grouping samples based on the dissimilarity between sets of observations, which can then be represented by Euclidean or squared Euclidean distance. The two most common methods of hierarchical cluster analysis are Average-Linkage and Ward's method (Baxter 2003, 91). This project will use Ward's method, which measures similarity by calculating the error sum of the squares, with distance between the points represented using squared Euclidean distance (Shennan 1997, 241; Baxter 2003, 92-3). It is the preferred method because, firstly, the dendrograms created are reported to be easier to interpret archaeologically (Baxter 2003, 92; Baxter 2001, 690) when compared to average-linkage diagrams (Baxter 2003, 93), and secondly, this is the most commonly used method in glass analysis, demonstrating that this technique can make archaeologically useful interpretations (Kato et al 2009; 2010A; Silvestri et al 2005; 2008). However, there are some downsides to Ward's method in that it can suggest structures even with random data and it is poor at identifying outliers (Baxter 2003, 93). Therefore, as suggested by Baxter, cluster analysis is used in conjunction with PCA and bivariate diagrams to visually confirm the identified groups. Furthermore, outliers were identified using alternative methods prior to cluster analysis and removed. Oxide selection is one of the most important determining processes in the successful use of cluster analysis. Baxter and Freestone (2006) note that the "*inclusion of variables that are not structure-carrying can hamper the detection of structure."* Therefore, variable selection took into account factors affecting each of the oxides involved. For example, structure created by geological (raw materials) and anthropological (recipes, additives) variables need to be recognised and identified so that archaeologically useful groups can be created and properly interpreted. The cluster analysis performed in this project will not use log-ratio data but utilise standardised data instead, as recommended by Baxter and Freestone (2006) who noted that standardised data tended to produce results that were *"more archaeologically interpretable"* (ibid, 524).

Principal component analysis (PCA) measures the co-variation between measurements, reducing the complexity of the data by producing an approximation. This allows many variables to be shown on a single plot (see Shennan 1997 265). Each principal component (PC) describes a certain percentage of the seen variation, the

higher the percentage, the better '*quality*' the approximation (Baxter and Buck 2000, 302). This technique enables large amounts of data to be compared visually in a single image. For this project only components with eigenvalues above 1 will be used, as recommended by Shennan (1997, 290), with the aim of using PCs describing the largest variation. As with cluster analysis, careful selection of the oxides was made. PCA bi-plots have been used in a number of glass studies, for example Baxter et al (1995; 2005); Freestone et al (2002B); Kato et al (2010A); Mirti et al (2009); Brill and Stapleton (2012). Both CA and PCA will be performed using the programme R (www.r-project.org).

As well as statistical techniques, a variety of graphical methods are employed, such as the use of bivariate diagrams of chosen oxides for the visual representation of groups. Bivariate plots have been used since the earliest glass research (e.g. Sayre and Smith 1974) to visually separate groups of data, and have been used successfully to demonstrate technological differences (Lilyquist et al 1993; Freestone 2006, 204), the separation of the principal natron groups (Freestone et al 2000) and plant ash groups (Henderson et al 2004; Freestone 2006, 204). Furthermore, the use of bivariate diagrams using oxide ratios allows some of the dilution effects to be neutralised and enables clearer distinctions between differing groups to be established (see Shortland et al 2007, 788). Bivariate plots, while simple, have the benefit of being conceptually straightforward and with utilisation of the correct oxides, very informative. This project will apply these to create groups for comparisons to literature data.

Line graphs make a second group of graphical methods and will be used particularly in the comparison of minor and trace oxides (e.g. Freestone et al 2002A; Walton et al 2009; Wedepohl et al 2011A; 2011B). For some trace elements, particularly the REE, to better identify distinctions due to raw material choice and not global abundances the data are normalised. For geological studies normalisation against chondritic concentrations is often used (Krauskopf and Bird 1995, 548). In glass research normalisation is commonly against the average crustal abundances (Wedepohl 1995), although in more recent papers weathered continental crust has been used (e.g. Jackson and Nicholson 2010; Walton et al 2009). This thesis will use values of

weathered continental crust as published by Kamber et al (2005) based upon alluvial muds from Queensland (MUQ).

5.4 Justification and Validity of the Methodology

The composition of glass is predominately a product of the raw materials and these in turn are principally affected by geology dictated by location, although anthropological and ecological factors also have impacts. Glass compositions can also be influenced by other factors that have the ability to blur the link between raw materials and the resultant glass. This has the potential to reduce the accuracy or even invalidate the use of glass chemistry in provenance. This section seeks to evaluate these other competing factors and to assess the validity of the methodologies outlined so far.

Is the composition of ancient glass representative of the raw materials used? The direct link between the raw materials and glass compositions has been disputed (Rehren 2000; 2008). Rehren (2000) explained that the raw materials employed to produce Late Bronze Age and Roman glass show a greater variability than demonstrated in the resultant glass. It was proposed that glass compositions tended to correspond to two eutectic troughs in the simplified soda-lime-silica system. Rehren noted that natron glasses are silica saturated, and fall into one trough, and plant ash glasses are calcium silicate saturated and fall into the second trough. He argued that the compositional range of a glass, in certain elements, was ultimately controlled by furnace temperature (ibid, 1277) and not by the raw materials. As well as the glass, a residual phase would be left as a by-product. Rehren concludes that *"major element concentrations are probably not suitable for provenancing the glass"* and that only elements that do not participate or affect melting behaviour should be used (*ibid*, 1331). Lime, alumina and silica act to raise melting temperatures and are therefore temperature dependent. This temperature dependence has been demonstrated under small scale laboratory conditions (Shugar and Rehren 2002).

In a similar vein the salt content (chlorides and sulphates) of the natron and plant ash can also act to alter the resultant glass composition (Rehren 2008). Excess chlorides and sulphates participate in glass formation by creating an immiscible phase in the melt, called a gall. These phases have been seen in ancient glass (Stapleton and Swanson 2002; Barber and Freestone 1990, 35-7). Na and K ion exchange between the glass melt and the gall result in a loss of potassium from the glass, lowering the potash content below the level implied by the plant ash. This effect has also been demonstrated experimentally (Tanimoto and Rehren 2008). Furthermore, the uptake of chlorine and sulphates is also governed by temperature due to their solubility in the melt (Bateson and Turner 1939). This limits Cl and SO_4 content to around 0.5-1.2% and 0.2-0.5% respectively in glass of the Roman and Byzantine period (Freestone 2006).

The effects highlight a need for careful consideration when selecting oxides for comparison. However, while partial melts have been demonstrated experimentally (Shugar and Rehren 2002) the impact on archaeological glass may be overstated. The crystalline residues from partial melts have yet to be recognised from Roman and later period production sites. Furthermore, the removal of this material from the glass would likely have been prohibitively time consuming in large scale processes and so production conditions would likely have be altered so that formation would have been avoided. Moreover, the premise that the lime content is limited by temperature assumes that the lime is in excess in the melt. For Byzantine production, this is not the case and it has been established that glasses can be separated into different populations using their major compositions using lime and alumina (Freestone et al 2000; 2002A; Foy et al 2003A; 2003B). Only during the Islamic period and the usage of plant ash with higher lime contents might temperature become a limiting factor. The formation of wollastonite phases in discarded glass from Tyre might be an example of this (Freestone 2002, 68). Hence the use of lime as a discriminator for plant ash glass will be handled with caution. The effect of salts on the potash composition of glass is also noted and glass groups will not be characterised solely by potash.

Contaminants from the melting chamber or crucible also have the potential to alter glass composition, where glass in contact with walls might take in additional amounts of silica, iron oxide, alumina, lime and other oxides. This is possibly evident to a limited

degree in analysed glass taken from furnace walls at Bet Eli'ezer (Freestone et al 2000, 77). Nonetheless, the large volume of glass versus the small area in contact with the furnace/crucible wall suggests such contamination would have negligible effect and this is particularly true for glass of interest here as tank furnaces were used for both primary and secondary glass working. Additional contamination could come from fuel ash. Experimental work by Paynter (2008, 280) demonstrated that vaporised potash from the wood fuel dissolved into the surface of the molten glass over time, while additional alkali enrichment was caused by ash falling into the melt, increasing the potash, magnesia and phosphorus oxide levels (ibid, 282). Glass enriched in magnesia and potash has been found archaeologically (Rehren et al 2010; Jackson and Paynter 2016; Freestone et al 2008A).

Two further effects can alter the composition of glass. Recycling can act to blur compositional groups and impart trace levels of colourant elements (see below). The addition of colourants themselves can also alter the glass composition. This is not just via the colourants themselves but also by associated elements. This project aims to avoid this effect by limiting the glass of this study to self-coloured, cobalt coloured and manganese de/coloured vessels.

To summarise, there are several factors that can affect the composition of glass which make some oxides more reliable discriminators of group and provenance than others. Careful oxide selection can limit these influences, in which case the use of compositional analysis in the creation of groups and the comparison of such groups to glass from other sites is a valid technique for the provenancing of glass.

5.5 Elemental Contributions

Previous work on glass compositional data has partitioned elements according to chemical affinities (Reade et al 2009; Shortland et al 2007) or by raw materials (Brems and Degryse 2014). This section will categorise and discuss the elemental contribution from each of the glass raw materials. Byzantine and Islamic period glass, as currently

understood, was made from sand (or quartz pebbles) fluxed with natron or plant ash. Lime was incorporated as a component of the sand or from the plant ash and was not added separately. This section will briefly discuss the chemical composition of the various raw materials and comment on which elements have been most suitable for provenance. The use of trace elements will also be discussed and how this is helping to shape the next stage of glass research.

5.5.1 The Flux

Ancient glasses in the near east are recognised to have been made using mineral soda and soda-rich plant ash from halophytic plants (Sayre and Smith 1961; Brill 1963; Freestone 2006).

5.5.1.1 Natron

Natron is the name of a sodium bicarbonate mineral ($Na_2CO_3.10H_2O$) but is also the common term for a group of sodium carbonate minerals (which also comprises some sulphate and chloride salts) from evaporitic lakes. The only yet recognised deposit in use by ancient glass makers is from the lakes of the Wadi Natrun, Egypt (Brill 1970; Devulder et al 2014; Shortland et al 2006A; Shortland et al 2011). An Anatolian mineral soda source has been suggested for later Byzantine glasses (Schibille 2011; Rehren et al 2015; see also Dardeniz 2015). Other potential mineral soda sites have been identified in Greece (Ignatiadou et al 2005; Dotsika et al 2009) and Libya (Devulder et al 2014). None of these sites have yet been confirmed for glass making.

The first analysis of natron connected to the study of glass was performed by Turner (1956B). Over the years a number of studies have sought to characterise the minerals present at the Wadi Natrun (Lucas 1912; Nakhla et al 1986; Taher 1999; Shortland 2004B). Rather than the mineral natron, it was established that the composition of Wadi Natrun natron was primarily trona, a hydrated sodium bicarbonate; $Na_2CO_3.NaHCO_3.2H_2O$ (Shortland 2004B), nonetheless, the term natron is in common usage and will be applied throughout this thesis. Other components of natron include the sodium carbonate mineral nahcolite as well as a combination of less beneficial sodium sulphates (thenardite, burkeite and mirabilite) and chlorides (halite; Taher

1999; Shortland 2004B; Shortland et al 2011). The Wadi Natrun is a collection of lakes and the inter-lake mineral complement has been shown to differ between lakes and also vary seasonally (Shortland 2004B). This would have affected the quality, quantity and seasonal availability of the natron.

Analysis has shown natron to be an extremely pure soda source with few impurities (Brill 1999B) apart from chlorine and sulphur, which, as discussed, only partially entersthe glass. Very few trace elements associate with the natron source, with only the elements B, P, Br and U appear in the same orders of magnitude in natron and the glass (Brems and Degryse 2014; Degryse and Shortland 2009). Other elements in the natron are found at several orders of magnitudes less than in glass, and so make a negligible difference – Li, K, V, Cr, Ni, Cu, Zn, Sr, Zr, Ba and Pb (Brems and Degryse 2014, 117). Similarly, the REE content of natron is insignificant compared to the sand (Wedepohl et al 2011B).

In summary, natron is a clean and clearly recognisable flux. It does not impart trace elements that would complicate other raw material contributions.

5.5.1.2 Plant Ash

Several plant species have been suggested as a raw material for glass-making (Turner 1956D; Brill 1970; Barkoudah and Henderson 2006; Tite et al 2006). The most common genera are *Salsola* (species *Salsola kali* and *Salsola soda*), *Salicornia*, *Suaeda*, *Haloxylon* and *Hamada*, within the Amaranthaceae family of plants. These are salt loving (halophytic) plants and various species can be found in coastal regions, salt marshes and in arid semi-deserts environments (Tite et al 2006; Barkoudah and Henderson 2006). The ashes of various plants have been analysed (Turner 1956D; Brill 1970; Brill 1999B; Tite et al 2006; Barkoudah and Henderson 2006), although a full and systematic investigation of compositional variation between plant species and location is still lacking.

For a plant ash to be useful for glass making it requires a high content of sodium and potassium as carbonates, bicarbonates, sulphides and hydroxides, and not chlorides or sulphates (Tite et al 2006, 1285). The suitability of a plant depends on the ratio of

alkalis (Na + K) to alkaline earth metals (Ca + Mg) as well as having a low chloride and sulphate content (Tite et al 2006; Barkoudah and Henderson 2006). Despite a large intra-species variation in composition it has been recognised that the ratio of Na/K is generally linked to plant species, for example *Salsola soda* has lower potash than *Salsola kali* (Ashtor 1992; Tite et al 2006, 1290; Barkoudah and Henderson 2006, 315).

There has been a number of attempts to match plant species to archaeological glass. Ashtor (1992), using analysis of coastal and semi-desert plants from areas of Israel, found *Salsola soda* to have the highest alkali and a Na/K ratio (5-6) most similar to archaeological glass. Tite et al (2006, 1290), using new analyses alongside previously published work, also found that *Salsola soda* and *Suaeda* from the Levant and Egypt were the closest Na/K match (~6.5) to ancient glass. Although, they noted that the Ca + Mg content of the ashes was relatively low. The other analysed species, *Salsola kali* (samples taken from Crete and Greece), did not match the Na/K ratio for Egyptian glass, and moreover the Mg + Ca content was too high for glass making, although they comment that this could have been altered by ash purification (Tite et al 2006, 1291). A final study by Barkoudah and Henderson (2006) also agreed that the *Salsola* genus had compositions most similar to archaeological glass (ibid, 319). They report that soda rich plants are more common than the potash rich ones, with compositions being relatively similar within species and this would probably have benefited glass makers (ibid).

Plant species affect ash composition, however, there are also other factors. Barkoudah and Henderson (2006, 320) demonstrated that calcium and magnesia in particular vary considerably within and between plant species, but this, they suggest, is predominately due to local geology. The higher magnesia content of Mesopotamian glasses has been suggested to have a geological link (Freestone 2006, 205) connecting the high magnesia seen in glass and glazes of Mesopotamian pottery (Freestone 1991) to possibly high magnesia in the alluvium of the region. Tite et al (2006) also report a higher chloride content in plants around salt marshes.

There are also non-geological/non-geographical considerations. Smedley and Jackson (2006; Jackson and Smedley 2008) has shown seasonal variation in the alkali content of bracken, and similar seasonal fluctuation may have affected Middle Eastern plant

species. Human factors can also have profound effects on the composition. Ethnographic studies of plant ashing in Pakistan (Rye 1976) found that the burning of plants in an open fire over a two-day period produced a range of products which were then graded. Analyses of different graded ashes by Tite et al (2006) found that higher grades contained more soda and potash, lower grades more calcium and magnesia. The differences were caused by higher temperature regions vaporising some of the more volatile compounds, particularly the potash which is lost at over 800°C (Misra et al 1993). This demonstrates that a range of compositional values could be produced even with plants of the same species and from the same region. Purification practices are another potential vector for variation. There is currently no direct evidence for ash processing in the Islamic period. However, as recorded from later Venetian practices (McCray 1998), ashes could be washed to dissolve out the soda and potash, which was then re-crystallized to produce a product from which the magnesia, lime and some of the iron oxide and alumina had been removed (Ashtor 1992, 492; Tite et al 2006, 1291; McCray 1998). Ashing techniques and any purification processes could therefore potentially have a significant effect on the resultant glass composition, although these are likely to be recognisable compositionally.

It is also a possibility that large quantities of plants of multifarious species were ashed together; in which case the resulting ash would fail to correlate compositionally to any particular plant species, but would represent an average of the plants collected in that specific region (Freestone 2006). In this case compositional differences would probably reflect the underlying geology.

The major elements that are imparted by the plant ashes are Na, Mg, K, P, Ca and varying levels of Cl and S (Brill 1970; Barkoudah and Henderson 2006; Reade 2009). Minor amounts of Al, Si, and Fe, plus trace amounts of Li, Rb, Cs, Be, Ba, Sr and the transition metals Ti, Mn, Cr, Cu, Ni, Zn are also reported (Barkoudah and Henderson 2006). The REE are present in insignificant quantities (<1 ppm; Barkoudah and Henderson 2006, 308-9) with Wedepohl et al (2011B) noting that the plant ash glasses are *“almost exclusively extracting REE from the quartz sands*.”

5.5.2 Silica Source

Silica is the largest raw material contribution to the glass by weight. For Roman and Byzantine natron glasses sand was the raw material of choice (see Freestone et al 2006). For Sasanian and Islamic plant ash glass there is increased debate and crushed pebbles have been suggested for some glass types (Brill 1995; Henderson et al 2004, 464; Henderson 2003A, 229; Mirti et al 2009, 1067). Due to the small ionic size of Si^{4+}, quartz is able to accommodate very few other elements into its crystal structure (Brems and Degryse 2014 117; Wedepohl et al 2011A, 89) resulting in elements associated with the silica source being primarily present as accessory minerals. These can include feldspar, pyroxenes, amphiboles, zircon, Fe and Ti oxides, monazite and clay minerals (Brems and Degryse 2014, 117; Wedepohl et al 2011A). The quantities of such minerals in sand vary between sand sources (Brems and Degryse 2014) and depend on the local geology. The broad range of oxides mean that sand is a suitable raw material for provenance. Quartz pebbles, while similar to sand, offer a much cleaner silica source with reduced quantities of accessory minerals. Tite et al (1998, 118) suggested that an iron oxide content <0.6% of Fe_2O_3 might imply use of crushed quartz over sand, however a number of sands with contents lower than this have been identified (Brems et al 2012).

Brill (1988), in a study of the glass from Jalame, Israel, provenanced the sand contribution of the glass to sand from the nearby River Belus, which demonstrates the potential of analysis to link glass to raw materials. Many studies have made use of oxides in the sand to characterise glass compositional groups and investigate provenance. Important major and minor element combinations have included Ca–Al (Freestone et al 2000; 2002A) in the identification of the natron glass groups; Al-Ti (Shortland and Eremin 2006) looking at Mesopotamian glasses; and Fe-Al (Brill 1995) in separating Islamic glass groups in Nishapur. It is also recognised that Egyptian sands have high levels of titania which have been used to identify Egyptian glass types (Picon et al 2008; Nenna 2014).

Although significant information has been derived from major elements, it is in the application of major and minor elements in combination with selected trace elements

where the most recent progress has been achieved. An evaluation of the usage of trace elements in Degryse and Shortland (2009) stated that elements deriving from the heavy minerals fraction of the sand, such as Zr, Ti, Hf and Sn, were most effective for provenance. These minerals are chemically resistant and less liable to weathering, and have a higher density, which would lead to increased variation by sorting. Reade (2009) proposed the use of what she termed the Sediment Related Elements (SRE), elements associated with sedimentary material. These include Al and Fe, and the minor and trace elements Sc, Ti, V, Cr, Y, Zr, Nb, Mo, Hf, Ta, W, Th, U and Tl. They are mainly found in the heavy mineral fractions of the sand and tend to correlate (Brems and Degryse 2014). This group is similar to Shortland's '*non-colourant highly correlated'* elements (Shortland et al 2007, 787).

Various studies have used different element combinations. In the field of Late Bronze Age glass Ti, Zr, La and Cr are used in the discrimination of Mesopotamian and Egyptian production (Shortland et al 2007; Walton et al 2009; Jackson and Nicholson 2010). Zr-Ti combinations has been used by Aerts et al (2003) to differentiate Levantine and Egyptian glasses, while a Zr-Sr-Ba combination has been used by Silvestri et al (2008) in investigating Roman glass, although Sr and Ba can also be found in manganese oxide ores used as a decolourant. Use of Zr-Hf, which is mainly found in zircon, and Nb/Ta ratios have similarly been used to discriminate glass groups (Wedepohl et al 2011A).

A combination of these SRE elements and those recommended in previous studies (Shortland et al 2007; Degryse and Shortland 2009) are utilised in this thesis to separate and confirm compositional groups and to make comparisons with other data sets.

5.5.2.1 Rare Earth Elements

The rare earth elements (REE) consist of the elements of the Lanthanide series, lanthanum to lutetium, atomic numbers 57-71. This group can be further divided into the Light REE (LREE) containing La-Sm and the Heavy REE (HREE) encompassing Eu-Lu (Krauskopf and Bird 1995). There are 15 elements in the Lanthanide series but

promethium is not found in nature, consequently only 14 elements are used. In addition, two further elements are normally added to this list: scandium (21) in the LREE and yttrium (39) in the HREE. They share similar physical and chemical characteristics (Degryse and Shortland 2009, 140).

The REE share certain similarities in their chemical and physical properties but also have a decreasing ionic radius with an increasing atomic number called the '*lanthanide contraction'*. This affects the elements distribution in geological material (Krauskopf and Bird 1995, 547). The LREE and HREE have different ionic sizes, and so are compatible with different minerals. In addition, Eu and Ce have two oxidation states (Eu 2+ and 3+; Ce 3+ and 4+) which produce positive or negative Eu or Ce anomalies under certain geological conditions. This can be used as a marker of geological origin. For example, Eu 2+ tends to be enriched in plagioclase feldspars giving plagioclase containing rocks a positive Eu anomaly (ibid, 548). These differences signify that REE can be used to investigate the geological history of igneous rock and as provenance indicators in sediments and sedimentary rocks (see references in Brems and Degyrse 2014).

The concentration of REE is low in quartz and principally accumulate in clays and in certain heavy mineral species such as monazite, allanite, zircon and garnet (see Wedepohl et al 2011B). The REE have successfully discriminated glass groups (Freestone et al 2002A; Mirti et al 2008; Silvestri et al 2008; Walton et al 2009; Jackson and Nicholson 2010) with Wedepohl et al (2011B) demonstrating significant differences in REE content within certain minerals. The LREE are enriched in monazite, while the HREE is enriched in heavier minerals, such as zircon. Degryse and Shortland (2009), on the other hand, found very little variation in the REE of Roman natron glass, concluding that the *"REE abundances and patterns do not seem to be correlated with the provenance, and thus be of little use"* (ibid, 140). They reasoned that the REE content of Roman natron glasses came from the clay fraction produced by the weathering of the regional geology, and was therefore homogenised over a large geographical area meaning there would be very little variation between sand sources.

The REE demonstrate a viable method for distinguishing glass groups and provenance, but are best utilised for glass of different geological regions, and/or if the REE is

influenced by significant quantities of heavy minerals from the sand. To aid the understanding of the REE results, values for the LREE/HREE ratio, Eu Anomaly and Total REE will be calculated. The LREE/HREE ratio is calculated by La/Yb and presents the relative difference between LREE and HREE levels. The Europium Anomaly is calculated by the formula $\frac{Eu}{\frac{1}{2}(Sm+Gd)}$ and indicates the strength of the Eu anomaly. Finally, the Total REE is the summed quantity of REE.

5.5.3 Colourants, Decolourants and Recycling

Most transition metals in sand are present in trace quantities (Brems and Degryse 2014, 128) but ancient glass often has levels exceeding this. Trace quantities can enter via the plant ash but the most significant contribution is through the addition of colourants, decolourants and opacifiers. Additives in use during the Islamic period included copper, lead, manganese, cobalt, tin and iron. Amounts tend to range from 500ppm (e.g. Co) up to several percent (e.g. Cu; Mn; see Turner and Rooksby 1959; Weyl 1976; Sayre and Smith 1974; Henderson 1985). For lead, larger quantities, up to 60-75% PbO, are found in certain glass types, e.g. Islamic emerald green glass (Brill and Stapleton 2012, 430). Antimony was also evidenced during the Roman period. These colourant elements are further associated with geochemically similar elements often present in the ores, such as zinc, nickel, silver, arsenic, tin, iron, among others. As discussed previously, the omitting of most coloured glass with the exception of cobalt and manganese de/coloured will act to minimise the occurrence of large quantities of transition metals, nonetheless, they can also enter glass though the addition of recycled glass (cullet) to a melt batch (discussed below).

Cobalt is a strong chromophore often added in quantities of only 500-2000ppm, cobalt ores also have a large range of associated elements. Principal contaminants, depending on the ore source, include Fe, Al, Mg, Ni, As, Sb, Cu, Zn, Pb and Sn. This large variation has led to the established recognition of a number of cobalt ore groups (Gratuze et al 1995; 2014; Abe et al 2012; Smirniou and Rehren 2013; Walton et al 2012; Kaczmarczyk and Hedges 1983, 41-54). These include potential sources from cobalt rich alum deposits in the Western Desert, Egypt (Kaczmarczyk 1986;

Kaczmarczyk and Hedges 1983) and the arsenic, nickel and iron rich cobalt ores thought to originate in Iran (Gratuze et al 1995; 2014, 323; Walton et al 2012).

Manganese oxide was a decolourant in frequent use during the Roman and Byzantine periods (Foster and Jackson 2010; Silvestri et al 2008; Foy et al 2003A). Although appearing diminish in use during the 7th-8th century (Freestone et al 2000), it once again became ubiquitous in Islamic period plant ash glass (Brill and Stapleton 2012). Manganese oxide tends to be a relatively impurity free ore source and is associated with fewer other elements but can include barium and strontium (Brill 1988, Jackson 2005, Silvestri 2008, 1498; Ganio et al 2012B; Cholakova et al 2016).

The act of glass recycling itself can also cause self-coloured glass to become contaminated with colourant related elements, occurring when cullet is added to fresh glass. While it is probable that the sorting of cullet would act to minimise the mixing of coloured and non-coloured glass in ancient times, quantities present as decoration – trails, prunts, coloured handles – or contained within previously recycled glass, would add small amounts of contamination. Such additions of coloured glass would act to enrich a batch in transition metals. Amounts of the colourants have been reported in the range of 50-2000 ppm, lower than deliberate additions but higher than the raw materials. This has allowed colourant elements to be suggested as indicators of recycling (Jackson 1996; Mirti et al 2002; Freestone et al 2002A). Therefore, any quantities of colourant elements above geological background levels indicate potential recycled glass unless high enough to be deliberate addition, which can be around 500ppm for cobalt, and from around 2000ppm for manganese oxide (see Chapter 7). The ability to recognise recycling is advantageous as it can help to explain anomalous ‘intermediate’ compositions or outliers, and can also facilitate greater understanding of how the glass supply in an area operated. This technique has been employed successfully to investigate glass recycling in the Roman and Byzantine periods (Jackson and Paynter 2016; Freestone et al 2015; Freestone et al 2002A), and the reuse of glass and supply in Anglo-Saxon period Britain (Freestone et al 2008B).

Chapter 6

Results: Natron Glass

This chapter will report the compositional characteristics of the natron glass and categorise the vessels into compositional groups. The identified groups will then be compared to known compositional types as defined in Chapter 5 in order to provenance the glass to production sites or regions. The raw materials, additives and any additional production information will also be identified and described at this stage. The natron and plant ash glass samples are considered separately due to the differences in raw materials, chemical make-up and production origins. Dealing with the technologies separately will make group assignations and literature comparisons easier to determine. Results of the plant ash glass are presented in Chapter 7. Four samples are omitted from further consideration at this time due to their being coloured with significant amounts of copper and lead oxides. They are discussed separately in Appendix K. This brings the total number of samples under consideration to 288. The full compositional results are available in Appendix H for the natron glass, and J for the plant ash glass, sorted by compositional group. Individual sample data and images can be found in Appendices C and D.

6.1 Separating the Natron and Plant Ash Vessels

Natron glass has been characterised as a low magnesia glass (LMG; Sayre and Smith 1974; Henderson 1985). Glass with magnesia and potash concentrations of less than 1.5% (Liliquist et al 1993, 56) have been typically called natron glass, while plant ash glasses, due to higher levels of both oxides in the plant ash, have contents in excess of this. Although, work by Schibille and Freestone (2016), Rehren et al (2010)

and investigations on recycling by Jackson and Paynter (2016) and Paynter (2008) have demonstrated that the magnesia and potash concentrations in natron glass can sometimes be higher than this. Nevertheless, the threshold of <1.5% magnesia and potash will be used as the basic criteria for distinguishing natron from plant ash glasses, and, as demonstrated in Figure 6.1, is capable of clearly distinguishing the majority of the glass. Four samples – JER 3835-08, JER 3835-10, RAM 4740-11, RAM-5947-20 – exhibit intermediate compositions with flux contents higher than most natron glasses but lower than a typical plant ash glass. At this stage these samples are identified as a-typical natron glasses (discussed in Section 6.6 and 6.7 below).

Of the 288 starting samples, 137 were identified as natron glass, including the four intermediate samples, and 151 samples as plant ash glass.

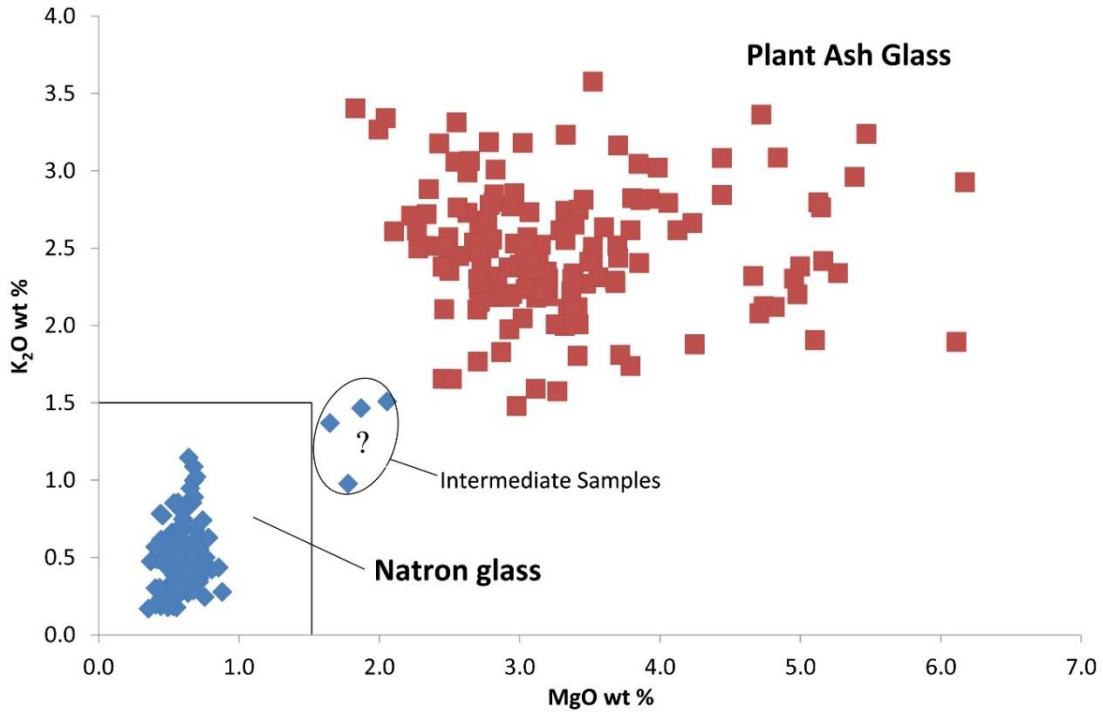


Figure 6.1. Graph of potash against magnesia. Natron glass region is identified at less than 1.5% of both oxides and the plant ash glass above this. Four exceptions are recognised, these are intermediate samples and are at this stage identified as a-typical natron glass. N=288.

6.2 Natron Group Characterisation

6.2.1 Assigning the Groups

The natron groups were assigned through an iterative process of Hierarchical Cluster Analysis (HCA) performed using different sets of oxides, alongside data exploration using PCA and bivariate plots. Ultimately 8 oxides were identified as being most useful in group identification and these were utilised to produce the finalised HCA depicting four main groups demonstrated in Figure 6.2. The chosen oxides provided the greatest separation between groups while still keeping the identified groups coherent. They also produced principal components with some of the highest percentage levels of explained variance. These oxides are SiO_2, Al_2O_3, CaO, SrO, Fe_2O_3, TiO_2, ZrO_2 and Na_2O. They represent the differences in glass composition due to, i) recipe through the use of soda and silica, and ii) sand source through alumina, lime, strontium oxide, iron oxide, titania and zirconia. These chosen oxides avoid elements which are potential recycling contaminants, e.g. flux and colourant oxides. Other oxides, particularly trace elements such as the sediment related elements (SRE), were potential choices, however, due to the geological similarity between the Levantine glass types (see below), the use of these elements hindered the separation of the two emerging groups, even if better separation was created between the other groups. Moreover, major and minor oxides have already demonstrated the ability to separate natron glass groups successfully in previous work (Freestone et al 2000; Freestone et al 2002A; Foy et al 2003A; 2003B). During HCA 8 samples were identified as outliers and omitted from Figure 6.2. They had intermediate or unique compositions which did not fit the identified groups. They are discussed separately in Section 6.6.

HCA divided the vessels into two main branches at around Dissimilarity 1100, as presented in Figure 6.2. Each of these branches then split into further sub-divisions at around Dissimilarity 200 to create two additional groups, categorising the vessels into four primary compositional groups: N-1, N-2, N-3 and N-4. No further sub-divisions between the samples could be justified (more details below). The elemental

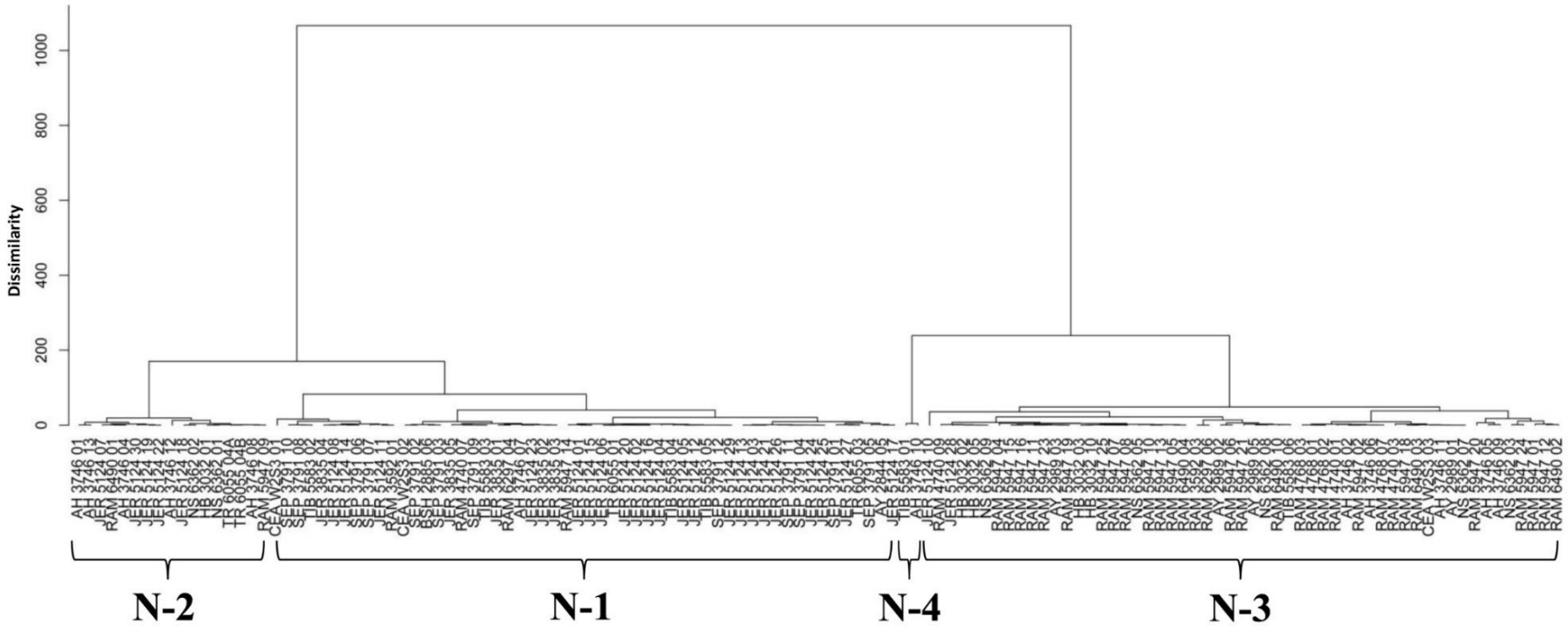


Figure 6.2. Cluster analysis (Ward's method) identifying the four principal natron glass groups. The determining oxides are SiO_2, Al_2O_3, CaO, SrO, Fe_2O_3, TiO_2, ZrO_2 and Na_2O. Eight natron glass samples were removed as outliers, see outlier category in Appendix H. N=129.

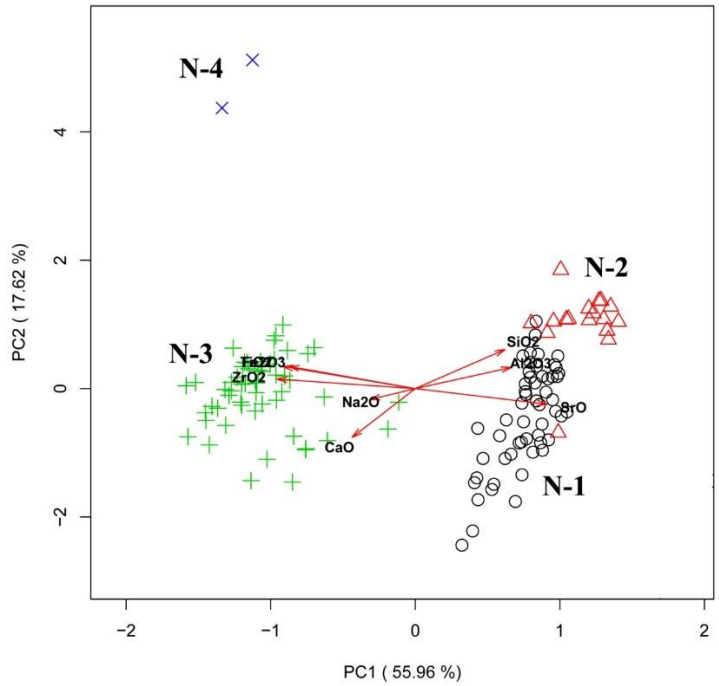


Figure 6.3. PCA bi-plot using Principal Components 1 and 2. The groups are created using the same determining oxides as used in Figure 6.2 and labelled using the same designations. Separation of the groups is demonstrated: N-1 and N-2 are higher in alumina, strontium oxide and silica, grouping to the right; N-3 and N-4 are higher in titania, iron oxide and zirconia, separating to the left. N=128.

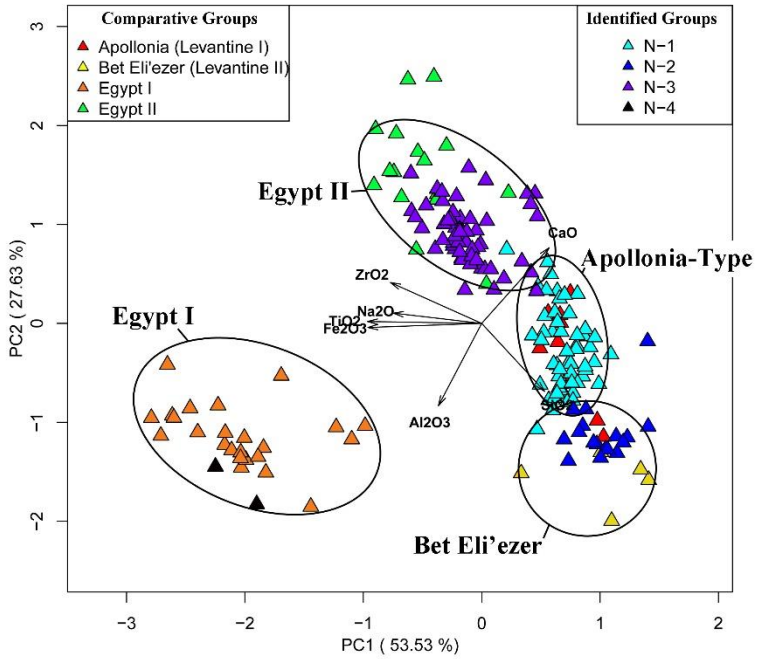


Figure 6.4. PCA bi-plot of the groups N-1, N-2, N-3 and N-4 compared against known literature types. Labelled circles added manually. Determining oxides as Figure 6.3 but omitting SrO (see text). Data is from primary production sites of Apollonia and Bet Eli'ezer (Freestone and Lankton pers. comms.; see Appendix A) and the Egypt I and II glass groups as found in Gratuze and Barrandon (1990).

weightings for these four groups are demonstrated using Principal Component Analysis (PCA) in Figure 6.3. Five Principal Components (PC) with eigenvalues >1 were identified. The eigenvalue is a number that describes the amount of variance within a PC, the higher the number, the more spread data is along a PC and therefore the more variance that is explained. PC1 and PC2 have the highest eigenvalues, and so explain the largest amounts of variation. 55.96% of the variation falls along PC1 which separates N-3 and N-4 to the left with high iron oxide, titania and zirconia, from N-1 and N-2 to the right with high strontium, alumina and silica. PC2 describes 17.62% of the variation, and further divides the groups with higher alumina and silica to the top of the bi-plot, and higher lime and soda to the bottom. N-3 is separated from N-4, which has lower lime and higher alumina; while N-1 is distinguished from N-2, which has lower lime and soda, but higher silica. The mean and standard deviations for the four primary groups are shown in Tables 6.1 (major and minor oxides), 6.2 (trace oxides) and 6.3 (REE oxides). Note that the N-3 group in these tables is presented by N-3*. This is a reduced group which has had five samples with deliberately added colourants omitted as these samples acted to skew the mean in some oxides, particularly in MnO, CoO and Fe_2O_3. The coloured samples are discussed separately in Section 6.5.

6.2.2 Comparison to Literature Groups

The four primary compositional groups identified in Figure 6.2 were compared against previously identified glass types in the PCA bi-plot in Figure 6.4. The comparative groups selected are LA-ICP-MS analyses of glass from the primary production sites of 6-7th century Apollonia (Levantine I; Tal et al 2004) and 7-8th century Bet Eli'ezer (Levantine II; Freestone et al 2000) by Freestone and Lankton (pers. comms; data in Appendix A), and NAA data from the Egypt I and Egypt II glass types from Gratuze and Barrandon (1990), as detailed in Chapter 3. Comparisons were also made to re-analysed data (LA-ICP-MS; Freestone and Lankton pers. comms.) of HIMT type glass from North Sinai (Freestone et al 2002B) and Carthage (Freestone 1994), however, no similarities were found and the HIMT data is not presented. The

Table 6.1. Mean (M) and standard deviations (S.D) of the major, minor and selected trace oxides for the four natron glass groups. Weight % unless indicated. Individual sample results in Appendix H.

Group	Glass Type	N	Colour†		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO‡	SrO‡	ZrO_2‡	BaO‡
N-1	**Apollonia (Levantine I)**	**54**	**pale blue**	**M**	**14.31**	**0.56**	**3.17**	**71.33**	**0.10**	**0.83**	**0.62**	**8.37**	**0.08**	**0.48**	**276**	**498**	**60**	**257**
				S.D	*0.96*	*0.08*	*0.18*	*1.51*	*0.05*	*0.09*	*0.17*	*1.19*	*0.01*	*0.07*	*436*	*48*	*8*	*21*
N-2	**Bet Eli'ezer (Levantine II)**	**17**	**pale blue**	**M**	**12.13**	**0.51**	**3.26**	**74.64**	**0.08**	**0.70**	**0.53**	**7.36**	**0.08**	**0.50**	**192**	**453**	**60**	**251**
				S.D	*0.90*	*0.08*	*0.21*	*0.80*	*0.02*	*0.07*	*0.12*	*1.08*	*0.02*	*0.11*	*26*	*38*	*11*	*18*
N-3*	**Egypt II**	**52**	**greenish-blue**	**M**	**14.14**	**0.58**	**2.53**	**70.48**	**0.10**	**1.03**	**0.29**	**9.51**	**0.26**	**0.92**	**359**	**218**	**235**	**174**
				S.D	*1.15*	*0.20*	*0.25*	*1.01*	*0.03*	*0.11*	*0.14*	*0.85*	*0.04*	*0.10*	*489*	*51*	*46*	*19*
N-4	**Egypt I**	**2**	**greenish-blue**	**M**	**17.06**	**0.83**	**4.46**	**70.94**	**0.08**	**0.98**	**0.43**	**2.71**	**0.54**	**1.79**	**405**	**219**	**255**	**229**
				S.D	*1.41*	*0.03*	*0.11*	*1.68*	*0.04*	*0.12*	*0.01*	*0.06*	*0.01*	*0.03*	*10*	*7*	*14*	*18*

† Most frequent colour; ‡ MnO, SrO, ZrO_2 and BaO as ppm; * Co and Mn de/coloured vessels removed from mean (5 samples)

Table 6.2. Trace oxide compositions for the four natron groups. Values as ppm. Li_2O, Se, Cd, In, Pt, Au are omitted as below detection limit.

		B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	Nb_2O_3	MoO	Ag	SnO_2	Sb_2O_3	HfO_2	Ta_2O_3	WO	PbO	Bi	ThO_2	UO_2
N-1	**M**	**206**	**17.1**	**35**	**2.1**	**5.4**	**27.0**	**13.2**	**4.1**	**3.2**	**10.3**	**2.1**	**0.41**	**0.05**	**9.1**	**bdl**	**1.30**	**0.11**	**0.07**	**54**	**bdl**	**1.04**	**1.09**
	S.D	*65*	*2.9*	*30*	*1.2*	*1.3*	*48.1*	*6.8*	*0.4*	*5.9*	*1.6*	*0.3*	*0.20*	*0.06*	*14.8*	*bdl*	*0.15*	*0.01*	*0.02*	*87*	*bdl*	*0.10*	*0.45*
N-2	**M**	**160**	**16.5**	**44**	**bdl**	**5.1**	**9.3**	**9.8**	**4.1**	**1.8**	**9.7**	**2.2**	**0.36**	**bdl**	**12.9**	**bdl**	**1.28**	**0.11**	**0.08**	**856**	**bdl**	**1.04**	**0.75**
	S.D	*38*	*2.8*	*49*	*bdl*	*1.1*	*13.1*	*3.3*	*0.5*	*0.5*	*1.7*	*0.4*	*0.11*	*bdl*	*22.2*	*bdl*	*0.19*	*0.02*	*0.01*	*2374*	*bdl*	*0.13*	*0.12*
N-3*	**M**	**270**	**35.7**	**51**	**3.7**	**7.6**	**17.9**	**22.7**	**3.7**	**2.3**	**5.0**	**4.5**	**0.18**	**0.11**	**14.2**	**bdl**	**4.98**	**0.25**	**0.09**	**92**	**0.09**	**1.82**	**1.14**
	S.D	*69*	*4.7*	*34*	*1.9*	*1.3*	*40.9*	*15.1*	*0.4*	*1.6*	*1.2*	*0.5*	*0.18*	*0.11*	*19.3*	*bdl*	*0.99*	*0.03*	*0.05*	*285*	*0.41*	*0.21*	*0.19*
N-4	**M**	**241**	**76.9**	**101**	**4.3**	**13.5**	**3.4**	**34.2**	**6.2**	**1.3**	**9.2**	**6.5**	**0.04**	**0.05**	**7.2**	**1.3**	**5.41**	**0.34**	**0.09**	**5**	**0.26**	**2.40**	**1.52**
	S.D	*52*	*0.6*	*4*	*3.9*	*0.3*	*1.0*	*0.0*	*1.0*	*0.0*	*0.3*	*0.0*	*0.04*	*0.03*	*9.2*	*1.7*	*0.02*	*0.03*	*0.00*	*2*	*0.35*	*0.16*	*0.04*

Table 6.3. REE values for the four natron groups. Values as ppm. Values for the Eu Anomaly, the La/Yb ratio (which compares the ratio of LREE to HREE) and the Total REE are also given.

Group		Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu Anom†	La/Yb	Total REE
N-1	M	9.1	8.4	16.0	1.91	7.5	1.51	0.43	1.28	0.22	1.30	0.28	0.74	0.10	0.68	0.10	0.31	12.30	49.5
	S.D	*0.7*	*0.8*	*1.6*	*0.13*	*0.5*	*0.12*	*0.05*	*0.13*	*0.02*	*0.11*	*0.02*	*0.07*	*0.01*	*0.05*	*0.01*			
N-2	M	8.7	8.2	15.8	1.87	7.4	1.47	0.42	1.29	0.21	1.24	0.26	0.69	0.10	0.68	0.10	0.30	12.16	48.4
	S.D	*0.7*	*0.9*	*1.8*	*0.16*	*0.5*	*0.12*	*0.06*	*0.12*	*0.02*	*0.10*	*0.02*	*0.06*	*0.01*	*0.06*	*0.01*			
N-3*	M	8.4	8.4	16.2	1.98	7.7	1.55	0.37	1.32	0.21	1.31	0.28	0.79	0.12	0.86	0.13	0.26	9.74	49.6
	S.D	*0.7*	*0.6*	*1.1*	*0.14*	*0.6*	*0.13*	*0.04*	*0.14*	*0.02*	*0.14*	*0.03*	*0.08*	*0.01*	*0.09*	*0.01*			
N-4	M	12.2	11.1	23.1	2.74	11.4	2.35	0.60	2.06	0.34	2.04	0.42	1.13	0.17	1.24	0.18	0.27	8.98	71.1
	S.D	*0.0*	*0.1*	*0.04*	*0.00*	*0.6*	*0.06*	*0.10*	*0.01*	*0.00*	*0.13*	*0.01*	*0.03*	*0.01*	*0.01*	*0.00*			

* Co and Mn de/coloured vessels removed from mean (5 samples)

† Eu Anom = Eu/(1/2(Sm+Gd))

Table 6.4. Mean and standard deviations of the major, minor and selected trace oxides of the four known literature groups. Weight % unless indicated.

Type	No.	Date	Analysis		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO*	SrO*	ZrO_2*
Apollonia-Type (Levantine I)[1]	10	6^{th}-7^{th} century	LA-ICP-MS	**M**	**14.51**	**0.64**	**3.03**	**71.60**	**0.08**	**0.83**	**0.49**	**8.14**	**0.08**	**0.46**	**195**	**495**	**53**
				S.D	*1.15*	*0.11*	*0.22*	*1.64*	*0.04*	*0.09*	*0.10*	*0.76*	*0.01*	*0.04*	*9*	*45*	*7*
Bet Eli'ezer (Levantine II)[1]	5	7^{th}-8^{th} century	LA-ICP-MS	**M**	**11.56**	**0.52**	**3.32**	**76.20**	**0.07**	**0.67**	**0.44**	**6.42**	**0.10**	**0.57**	**189**	**418**	**59**
				S.D	*1.18*	*0.03*	*0.18*	*1.22*	*0.01*	*0.12*	*0.11*	*0.77*	*0.04*	*0.21*	*30*	*50*	*11*
Egypt I[2]	24	7^{th}-8^{th} century	NAA	**M**	**18.25**	**0.93**	**4.05**	**70.05**	**n/a**	**0.95**	**0.40**	**3.03**	**0.50**	**1.74**	**514**	**n/a**	**246**
				S.D	*1.38*	*0.14*	*0.29*	*1.21*	*n/a*	*0.14*	*0.11*	*0.23*	*0.12*	*0.28*	*70*	*n/a*	*65*
Egypt II[2]	17	8^{th}-9^{th} century	NAA	**M**	**17.26**	**0.58**	**2.19**	**67.85**	**n/a**	**1.07**	**0.32**	**9.34**	**0.27**	**0.98**	**302**	**n/a**	**220**
				S.D	*1.96*	*0.13*	*0.35*	*1.90*	*n/a*	*0.18*	*0.24*	*1.27*	*0.06*	*0.23*	*146*	*n/a*	*80*

1 Data from Freestone and Lankton (pers. comms.; see Appendix A).

2 Data from Gratuze and Barrandon (1990)

*ppm

determining oxides are as Figure 6.3, however SrO was omitted as it was not available for the Egyptian reference samples.

The PCA comparison demonstrated close similarity between the identified groups and known literature groups. Groups N-1 and N-2 are identifiable as Levantine glass, with group N-1 corresponding to Apollonia-type (Levantine I) glass and N-2 to Bet Eli'ezer production (Levantine II). Groups N-3 and N-4 was a match to the Egyptian glass types, with N-3 correlating to Egypt II, and the two samples of N-4 closely resembling Egypt I.

6.3 The Levantine glass – N-1 and N-2

Groups N-1 (54 samples) and N-2 (17 samples) comprise two sets of very similar glass. They are of similar colour, mainly pale blue (aqua) but greenish-blue on occasion, and chemically, both are characterised by sand sources low in oxides from heavy accessory minerals (averages of 0.08% titania, 0.48-0.5% iron oxide, 60ppm zirconia; Table 6.1) and low quantities of REE, as well as a pronounced positive europium anomaly (Table 6.3). In addition, both glass types have markedly low quantities of the trace elements Nb, Hf, Ta and Th (Figure 6.5). The trace element distributions demonstrate that the two groups are extremely close geochemically, with no clear recognisable differences. This is logical, as the sands used are from a similar geological setting. The sites are just 40km apart, and although Apollonia is coastal and Bet Eli'ezer inland, the geochemistry of the sands from both sites are dominated by the outflow of the Nile. Sediments from the Nile, carried within the Nile littoral cell, are deposited across the Levantine coast (Freestone 2006, 206), while the geological influence of inland material is minor (Goldsmith and Golik 1980, 530). The association between the Nile outflow and sediment deposits in Israel is recognised in the neodymium isotope values for the Levantine coastal sands, which is very high ε_{Nd} at -4 to -5 (Freestone et al 2009B, 36). This is close to the ε_{Nd} value of -2 in Nile sediments, a result of weathering material from young volcanic rock from the Ethiopia highlands (ibid, 37). It contrasts with the lower values (down to ε_{Nd} -13) in the Western Mediterranean, which is a

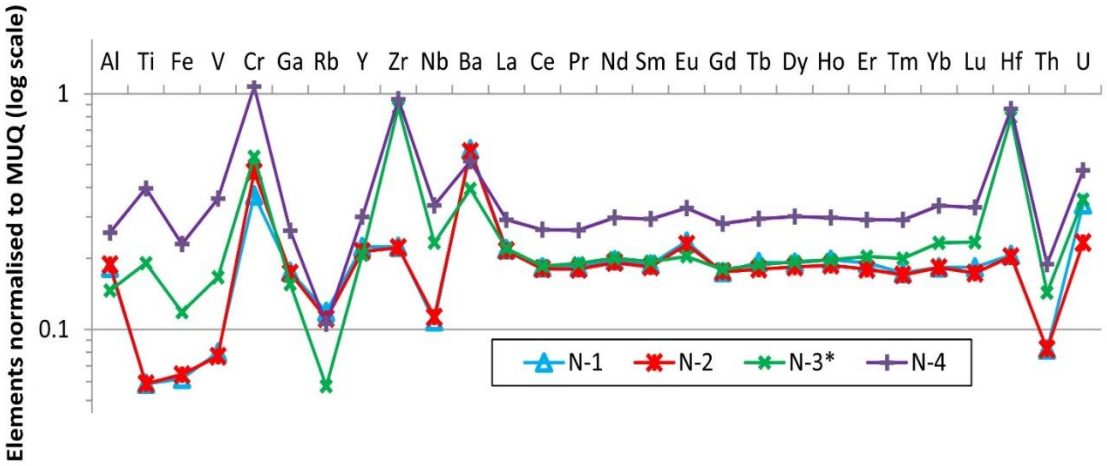


Figure 6.5. Selected trace and REE data of the four natron glass groups. Data normalised to weathered continental crust (MUQ; Kamber et al 2005). N-3 = reduced group with coloured samples removed. Graph demonstrates trace elemental differences between the Levantine (N-1 and N-2) and the Egyptian (N-3 and N-4) glass types.*

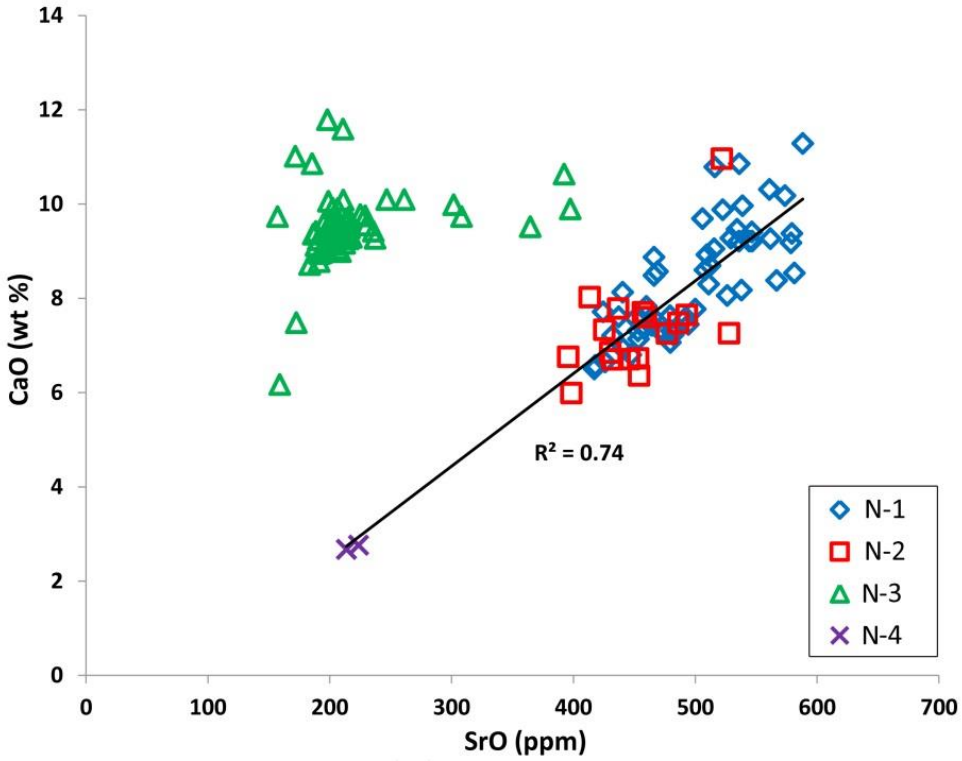


Figure 6.6. CaO against SrO. Trend line includes groups N-1, N-2 and N-4 indicating a positive correlation and suggesting a shell source for the lime content. N-3 does not show this, suggesting a limestone source.

result of much older weathered material coming from Europe and North Africa (Degryse 2014, 54).

In the major oxides, N-1 and N-2 are relatively high in alumina (>3%) and low in iron oxide, suggesting a mature, high silica sand with a significant feldspar content. They are also rich in lime (7-9%) and strontium oxide (~500ppm), with a strong correlation between the two (Figure 6.6). This suggests, as recognised by Freestone et al (2003), that these glasses were made of a marine sand with the lime predominately present as shell. This is because strontium is able to substitute for calcium within the mineral aragonite, the main constituent of shell, but not in calcite, the mineral constituent of limestone (ibid, 21).

Due to their geochemical similarity, discriminating N-1 and N-2 is only possible using a few major oxides. Freestone et al (2000) demonstrated that soda and silica, oxides specifically linked to the glass recipe (i.e. flux/sand mix), and lime and alumina, which reflect differences in the carbonate (shell) and feldspar contents of the sand deposits (cf. Brill 1988), can act as good discriminators, as presented in Figure 6.7, a bi-plot of CaO/Al_2O_3 against Na_2O/SiO_2. While some similarity is shown between the vessels, there exists a clear distinction between the two groups; Group N-1 has a generally higher Na_2O/SiO_2 ratio, which is a result of the higher average soda values and lower silica in N-1 (14.3%/71.3%) compared to N-2 (12.1%/74.6%).

The respective ranges for the silica contents are 66-73% for N-1, and 73-76% for N-2, demonstrating a larger spread in N-1, this is greater than the range in soda. For example, the variance of soda in N-1 is 0.96, while silica is 1.51. Therefore, the variation in silica is caused by more than the recipe alone but also due to variation within the sand source. In Figure 6.7 this is seen as a wide spread in the lime/alumina ratio of N-1. Alumina has a low variance and therefore this is due to the lime content. Average lime values in N-1 is slightly higher (8.37%) than N-2 (7.36%) but the spread in N-1 is larger at 6.5-11.3% compared to 6.0-8.0% in N-2 (this excludes AH 3746-12 with 11.0%). From this we can conclude that the N-2 type glass uses a source lower in lime

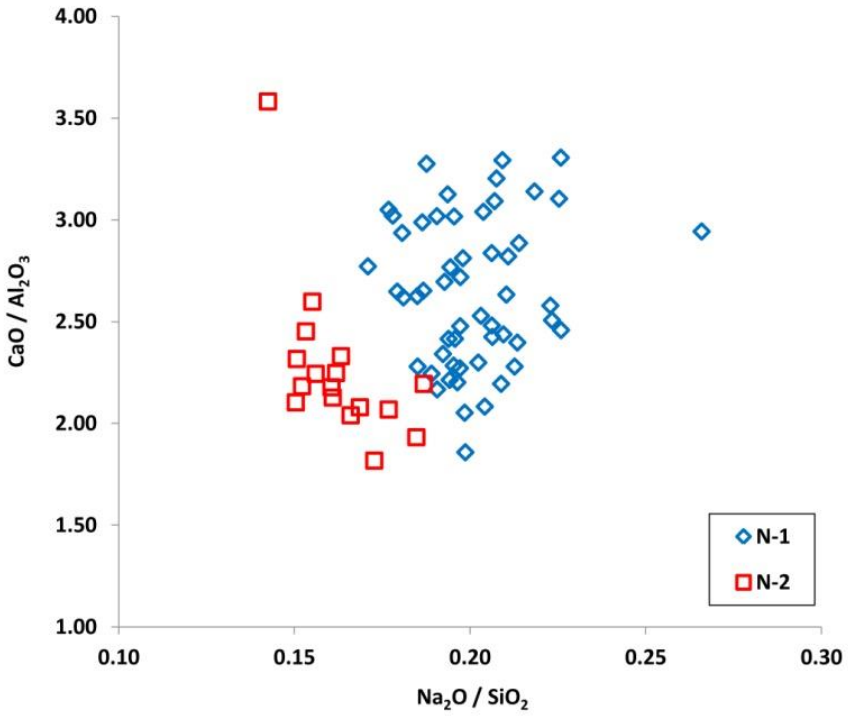


Figure 6.7. Graph demonstrates the separation between the Levantine groups (N-1 and N-2) mainly around the soda/silica ratio. Note also the larger spread in CaO/Al_2O_3 as seen in the N-1, mainly due to variations in the CaO.

but also with lower internal variation. This could be because N-1 uses sands with greater differentiation within the same deposit but it could also reflect batches from different locations or even changes in the sands through time. These latter suggestions have the potential to be archaeologically significant.

The possibility of chronological and spatial compositional variation is investigated in Figure 6.8 (a & b). Figure 6.8a presents the N-1 and N-2 vessels grouped by site, however, no obvious correlation between composition and location is observable, with one exception, there is a tight concentration of N-1 glass from Jerusalem (site A-5124), although this is not an exclusive group. This tight cluster might represent a glass batch or the output of a particular workshop (see Freestone et al 2009A), but it does not indicate a unique or exclusive production group. A few other sites reveal samples displaying close similarity, for example two samples each from Nahal Shoval, Tel Rosh and Ahihud, but there are no indications that compositions are spatially determined.

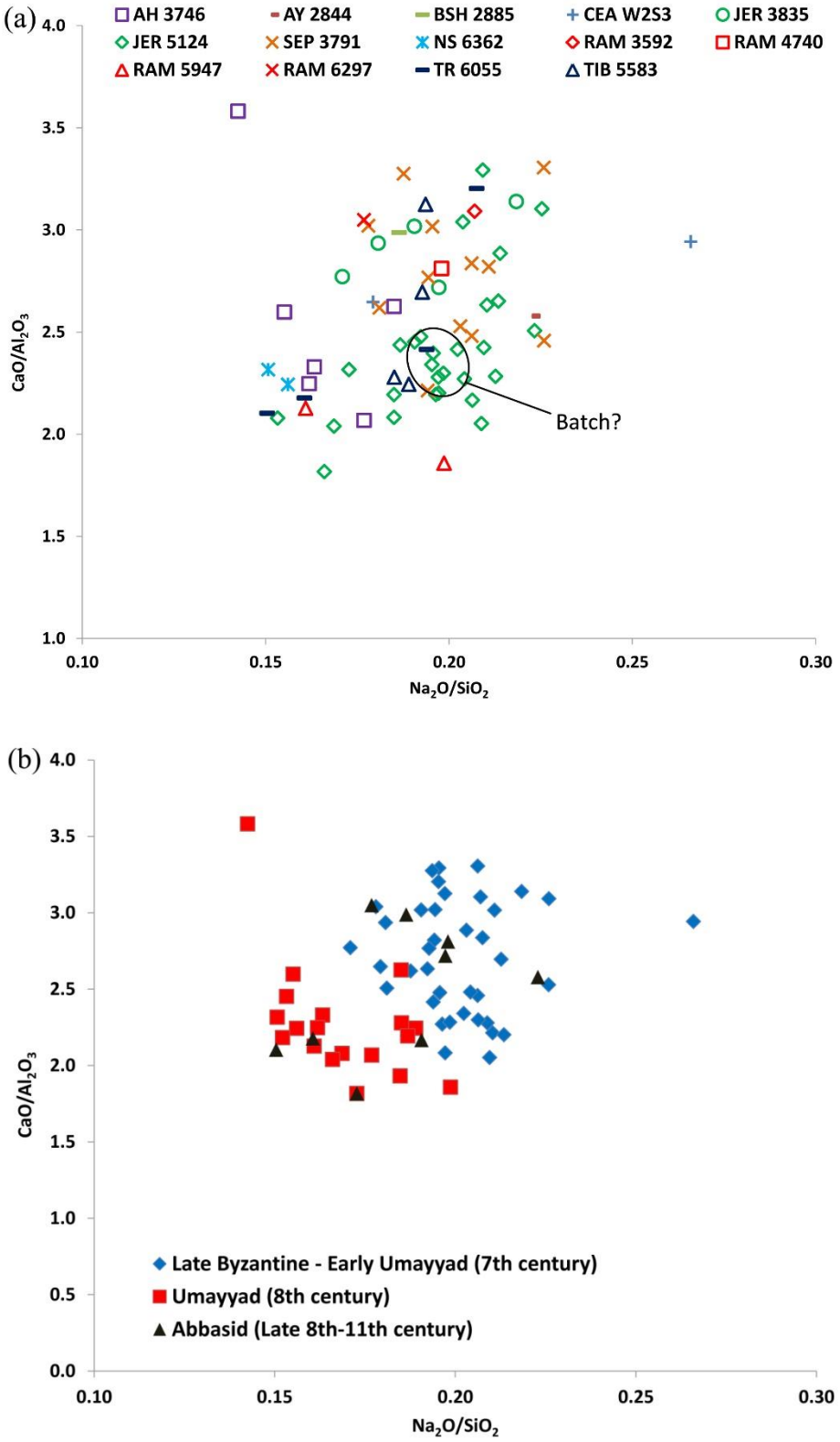


Figure 6.8. Graphs of CaO/Al_2O_3 against Na_2O/SiO_2. a) Samples grouped by site. No correlation between composition and location is seen except for Jerusalem (A-3535), in which a tight cluster possibly suggests a glass batch. B) Samples grouped by date, with lower soda and lime in the 8th century Umayyad period glass.

Figure 6.8b plots the same vessels sorted by date. There is a definite trend in the Umayyad 8th century towards lower soda/silica ratios, demonstrating a change to lower soda recipes at this time. No clear difference is seen in the alumina/lime ratio within the N-1 group, although later periods seem to lack vessels of the highest CaO/Al_2O_3 ratios. Nonetheless, no clear chronological link to sand source is noted.

Major and minor oxide comparisons against various literature data are shown in Figures 6.9 and 6.10. The first compares samples from primary production sites, and includes data from 6-7th century Apollonia, the 4th century Jalame, and 7-8th century Bet Eli'ezer. The first two of these sites have been grouped as Levantine I glass, and glass from Bet Eli'ezer as Levantine II (Freestone et al 2000). It is observed that group N-1 most closely corresponds to Levantine I production from the site of Apollonia and much less so to material from Jalame (Weinberg 1988), although the N-1 data does show a degree of overlap with the material from Jalame. Overall, however, it demonstrates a definite difference in the sands, with the bulk of N-1 more likely to have been produced close to the site of Apollonia, using similar sands, rather than to Jalame which possibly sourced sands from the Bay of Haifa (Brill 1988). The Jalame samples tend to contain higher lime and lower alumina when compared against average data from Freestone et al (2000) and Tal et al (2004), as discussed in Chapter 3. N-2, in contrast, most closely resembles Bet Eli'ezer production, and shows a very close overlap, sharing lower levels of lime, much lower soda and higher silica, implying a recipe similarity and the same sand source, suggesting production in the same or similar area. Note that 6 samples from the Bet Eli'ezer production site do fall within the Apollonia and Jalame regions, however, how much this is due to poor mixing within the furnace (these samples are glass taken from the furnace wall) and therefore not representative of vessel glass is unknown. It can be reasoned that upon re-melting for vessel shaping such heterogeneity would be averaged out.

Figure 6.10 compares N-1 and N-2 with a selection of known Levantine glasses from a variety of Eastern Mediterranean sites dating from the late 4th to early 9th century. The samples come from consumption sites (e.g. Petra, Jordan) and also secondary workshops (e.g. Raqqa, Ramla), as well as the known primary production sites. As before, N-2 matches production from Bet Eli'ezer and shows no overlap with any other

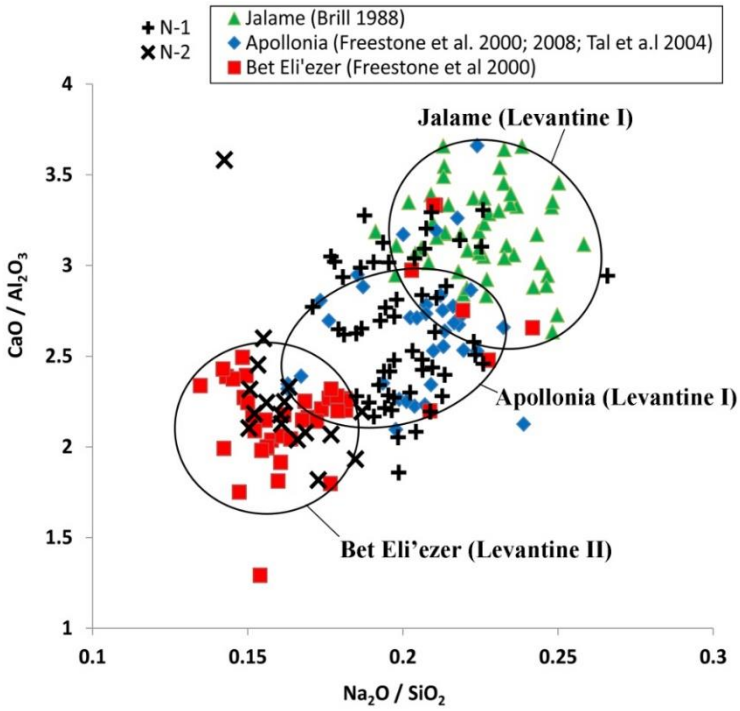


Figure 6.9. The Levantine groups (N-1 and N-2) are presented against comparative data from the three known primary production sites in Palestine: 4th century Jalame; 6-7th century Apollonia and 7-8th century Bet Eli'ezer. Data sources in key. Circles added manually to highlight production spreads. N-2 falls mainly into Bet Eli'ezer region and N-1 into Apollonia. Graph demonstrates overlapping but distinct productions at Apollonia and Jalame.

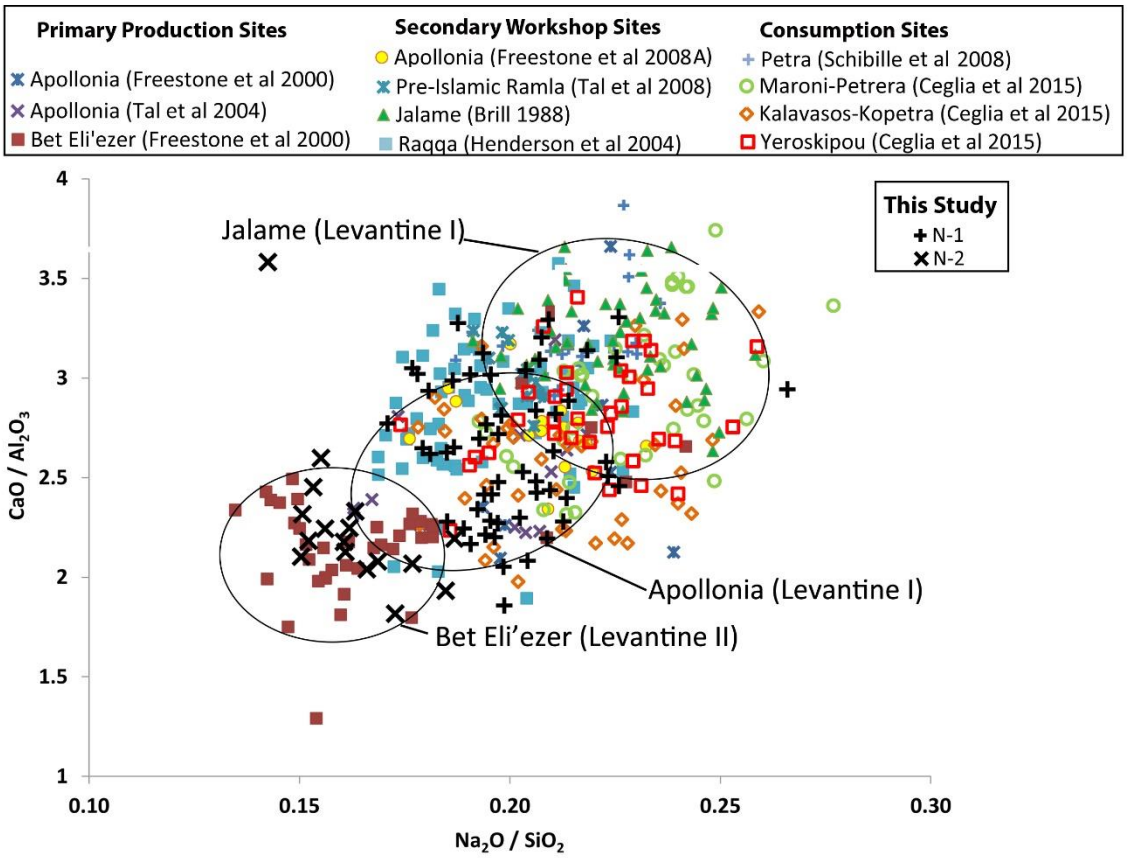


Figure 6.10. Graph comparing the Levantine groups against literature data from primary and secondary production sites, and consumption sites. Data sources shown in key. N-2 is similar to Bet Eli'ezer glass only, while N-1 has a wide spread, covering the Palestinian sites but also the Levantine glass from Raqqa and glass from some sites within Cyprus.

sites. The N-1 material, as well as corresponding with production from Apollonia, overlaps with glass from consumption sites in Cyprus, particularly the glass from Kalavasos-Kopetra dating to the 7th century (Ceglia et al 2015). Some of the N-1 samples also show similarity to some of the Raqqa Levantine glass (Raqqa Type 3) dating to the late 8th-early 9th century, a type which tends to have particularly high lime/alumina ratios and lower soda/silica ratios.

To further reinforce the concordance between the N-1 and N-2 groups and the Levantine reference groups, a line graph of selected major, minor and trace elements normalised to MUQ is presented in Figure 6.11a (Levantine glass) and b (Egyptian glass). All the data used is LA-ICP-MS reanalysed samples by Freestone and Lankton (pers. comms; see Appendix A). The Levantine glass is represented by samples from Apollonia and Bet Eli'ezer and the Egyptian glass by 4 samples of Egypt II type glass from El Ashmunein (Bimson and Freestone 1985). There is no reference data for Egypt I glass with this range of elements, so HIMT data is used to represent additional Egyptian production. These are samples from North Sinai and Carthage (Freestone et al 2002A; Freestone 1994). Visual comparisons of N-1 and N-2 to data from Apollonia, Bet Shean and Bet Eli'ezer show a consistently close correspondence in profile and abundance, absolute quantities of REE are low, and they all share a pronounced positive Eu anomaly, and no Ce anomaly. There are particularly pronounced dips at Nb and Th observable in both glass groups. Ba however, is quite high, and is one of the few elements to be higher in the Levantine glass compared to the Egyptian glass groups (not including HIMT). However, some slight differences can be detected between the current and literature groups, where the quantities of Cr in N-1 and N-2 are higher in the former than the latter, although this might be in part due to the high variability in Cr, for example, the coefficient of variation for Cr_2O_3 is approximately 90% for N-1 and N-2. Bet Eli'ezer has a smaller positive Eu anomaly than the other Levantine glass types, and there is a slightly larger difference in Lu and Zr between N-1, N-2 and, to a lesser extent, Bet Eli'ezer as compared to Apollonia. One possible reason for these modest differences is that the glass from consumption sites (N-1 and N-2) may have been subjected to more contamination from the REE in the furnaces compared to the glass from primary production sites which may have only been

melted once. This might explain the higher total REE levels in N-1 and N-2 (49.5 and 48.4ppm) compared to the glass from Bet Eli'ezer (46ppm) and Apollonia (45ppm), although this difference is slight. Note, however, that comparisons of the total REE between fresh and recycled glass in Section 6.6 below do not appear to indicate a link between recycling and total REE.

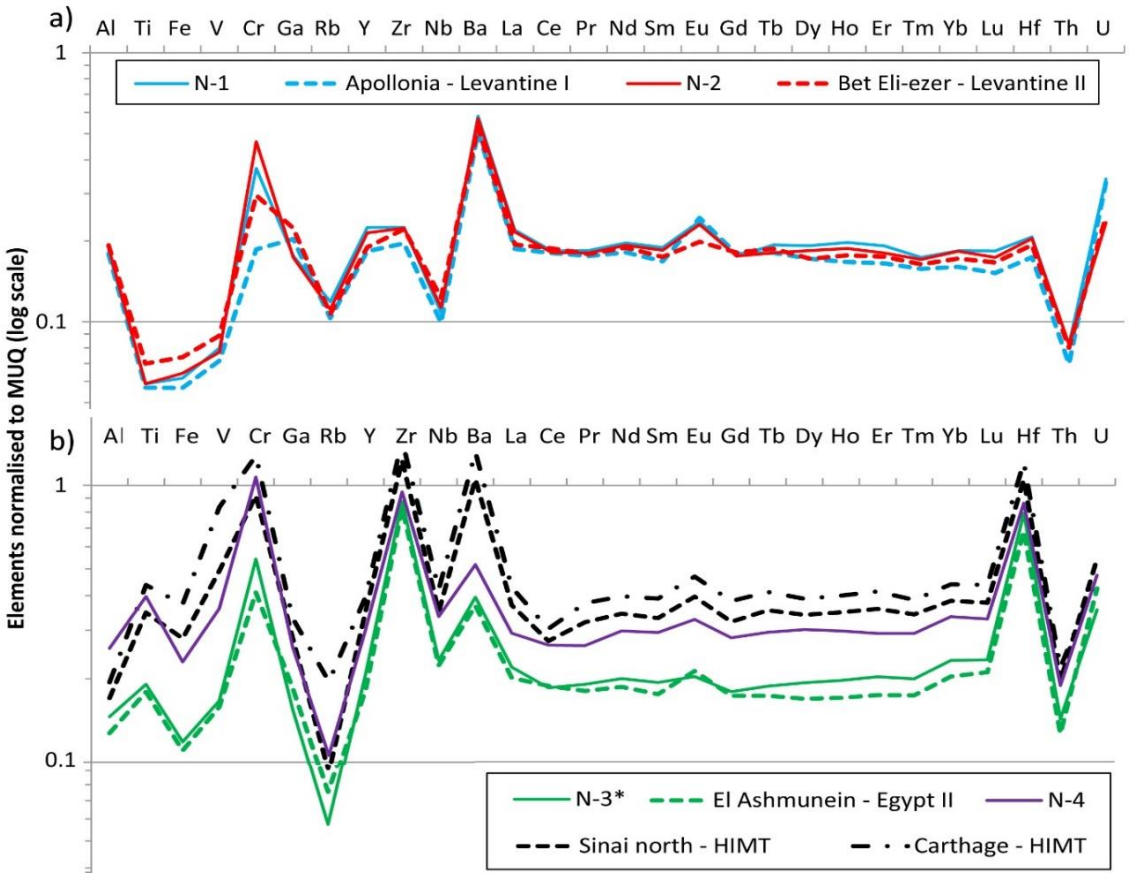


Figure 6.11. Line graph of selected sand elements. Values are normalised to MUQ (Kamber et al 2005). a) the Levantine glass groups (N-1 and N-2) are presented against data from Apollonia and Bet Eli'ezer (Lankton and Freestone pers. comms.; Appendix A). b) the Egyptian glass groups (N-3 and N-4) compared against Egypt II glass from El Ashmunein and HIMT glass from North Sinai and Carthage, all data Lankton and Freestone pers. comms. (Appendix A). Clear distinctions can be seen between glass of the two regions, indicating geochemical and minerological differences.*

6.4 The Egyptian Glass – N-3 and N-4

N-3 with 57 samples and N-4 with 2 samples are both Egyptian glass types, and share certain similarities (note that this section will use a modified average of N-3* where five deliberately coloured samples have been omitted.) N-3 and N-4 are characterised by sand sources much higher in the heavy accessory minerals than the Levantine glass (N-1 and N-2), and show considerable quantities of iron oxide (1-2%), titania (0.3-5%) and zirconia (200-300ppm; Table 6.1). There is also relative enrichment in some of the heavier trace elements, Nb, Hf, Ta, Th and U (Figure 6.5; Table 6.2) and in the REE, with N-3* and N-4 having a higher complement of HREE compared to the Levantine glass (Table 6.3), as demonstrated by a lowering of the La/Yb ratio in Figure 6.12. Wedepohl et al (2011B) demonstrated that HREE is elevated in minerals such as zircon and rutile, both of which are present in substantial amounts in the N-3 and N-4

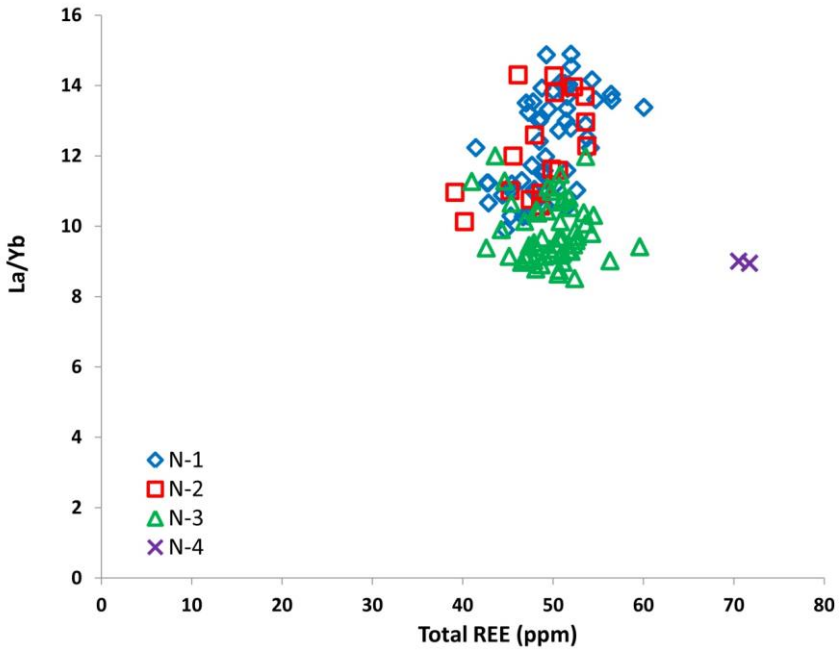


Figure 6.12. Graph showing the relationship between LREE/HREE ratio and Total REE. N-4 has the highest total REE and the Egyptian glass (N-3 and N-4) have an increased HREE content compared to the Levantine glass.

glass. N-4 is particularly rich in REE, with much higher Total REE than the other groups, including N-3*. It has also been noted that iron oxide and titania are typically high in Egyptian sands and in Egyptian glass (Nenna 2014, 179; Foy et al. 2003A, 45; Picon et al 2008), and so the characteristics of N-3 and N-4 match those of other Egyptian types. Soil and sediment samples taken from areas of the Nile and the Delta confirm this picture with generally enhanced amounts of Ti, Zr and Hf in sediments (Arafa et al 2015, 59). Furthermore, the raised soda content seen in N-3 and N-4 is also typical of Egyptian glass, which is found to be higher than Levantine glass of the same date, probably due to the close proximity to the natron source. This is demonstrated in Table 6.4, where the Egyptian glass averages have approximately 3-7% more soda than Levantine types.

Despite their shared Egyptian origin, N-3 and N-4 are distinctly separate glass groups comprising different raw materials. N-3 vessels are predominately greenish-blue to green in colour and made of an Egypt II type glass. The similarity to Egypt II glass is

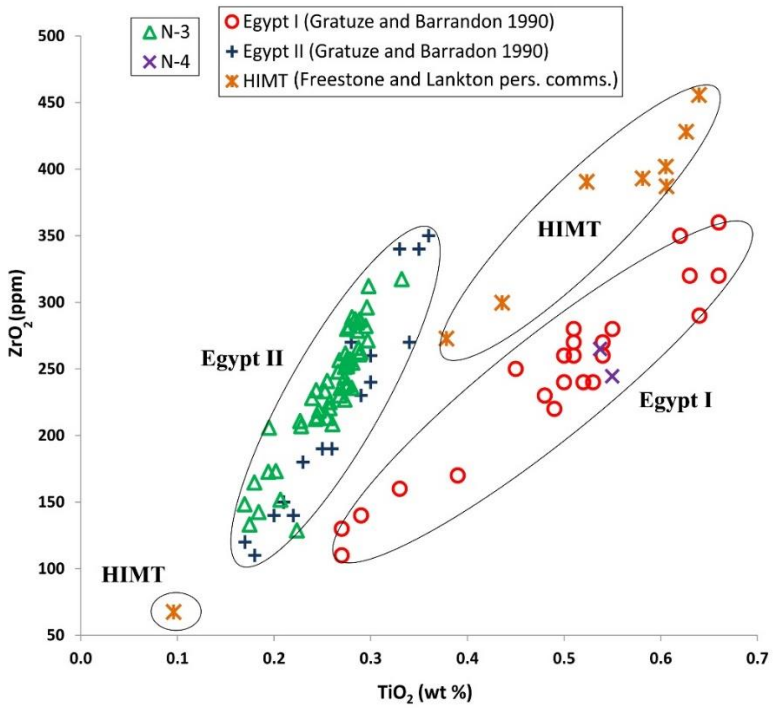


Figure 6.13. Comparison of the Egyptian glass groups (N-3 and N-4) against known types, Egypt I, Egypt II and HIMT, using ZrO and TiO_2. HIMT samples from North Sinai (Freestone et al 2002A) and Carthage (Freestone 1994), data source in key. N-3 shows similarity to Egypt II, and N-4 to Egypt I. Neither glass matches HIMT types.

demonstrated by comparison to reference material in Figure 6.4, and is further confirmed by the close similarity in ZrO_2/TiO_2 ratio as demonstrated in Figure 6.13. In major oxides, N-3 is characterised by relatively low amounts of alumina (2-3%) and high lime (9-10%), matching the literature data for Egypt II shown in Table 6.4. N-3 has low amounts of SrO resulting in a particularly low SrO/CaO oxide ratio. There is also a lack of correlation seen between these oxides, as shown in Figure 6.6, suggesting that, unlike the other glass types, the lime is derived from a limestone source rather than beach sand (Freestone et al. 2003). The production origins of this group are unknown, but in addition to coin weights from Fustat (Gratuze and Barrandon 1990), other appearances of this glass type include a secondary workshop at El Ashmunein, Middle Egypt (Bimson and Freestone 1985), 61 samples of Kato's N2-b group from Raya, South Sinai, dating mainly to the 9th century (Kato et al. 2009, 1705), and 18 samples of Abbasid dated glass from Tebtynis and Fustat, Egypt, labelled as Group 7 (Foy et al 2003B).

Finally, N-3 includes the only natron glass vessels analysed with added cobalt or manganese. Three samples were dark blue with added cobalt and two samples contained added manganese oxide. These are discussed later.

N-4 consisted of only 2 samples, greenish-blue in colour, and of a very distinctive composition matching Egypt I type glass as indicated in Figure 6.4. This is further demonstrated in the ZrO_2/TiO_2 ratio in Figure 6.13. N-4 has the highest levels of iron oxide (av. 1.8%), titania (av. 0.5%), and alumina (av. 4.46%) of any glass group, however, lime is distinctly low (av. 2.7%), as is strontium oxide. The SrO/CaO ratio corresponds with that of groups N-1 and N-2 (Figure 6.6) suggesting that the lime is from shell-containing coastal sands, although the shell/silica ratio of the sand was appreciably lower than that of the sand applied in the Levantine glass. The production origins for Egypt I glass have been attributed to the Wadi Natrun (Freestone et al. 2000, 72) due to compositional similarities to glass waste from that area described by Sayre and Smith (1974). Roman glass with low lime has also been identified from this locality by Picon et al (2008), although current production evidence is from the Roman period and no glass working debris for the Islamic period have yet been uncovered (Nenna 2014). Production in the Egyptian Deserts outside the Delta might also be a

possibility, with the data suggesting a coastal location or at least access to sands with a significant shell content. N-4 is also similar to Foy et al's (2003B) Groups 8 and 9 dating to the Umayyad period from Tebtynis and Fustat, these are also most likely of Egypt I production.

As with the Levantine glasses, Figure 6.11b compares the selected major, minor and trace elements of the Egyptian groups to literature and known groups. Egypt II is represented by re-analysed material from El Ashmunein (Freestone and Lankton pers. comms.), and although there are no data for Egypt I, HIMT data is presented from late Roman Carthage and 5th century North Sinai. The figure demonstrates an almost identical match in profile and abundance between N-3* and Egypt II. As noted, distinctive characteristics of this glass include high Ti, Fe, V, Zr, Nb, Hf, Th, while the Rb and Ba content is much lower than the other glass types. N-4 was consistently higher than N-3 in most elements. Comparisons with HIMT showed some similarity, suggesting that a shared geological origin could be possible despite their differences in major and minor elements. Although the REE abundance in N-4 is dissimilar to the substantial levels in the HIMT glass, the profile is the same. There are some other differences; HIMT glass indicates a small negative cerium anomaly not seen in N-4, or any of the other glass group. HIMT also has particularly raised levels of Ba, although this might be connected to raised Mn content of this glass type. In the other trace elements, N-4 shows particular abundances in Ti, Cr, Nb, Hf and U.

6.5 The Coloured Glass

Five samples had cobalt or manganese in quantities signifying deliberate addition. All of these vessels had a N-3 (Egypt II) base glass. Three samples (RAM 3592-03, RAM 6297-06 and TIB 5583-06) are dark blue with added cobalt (here labelled N-3 Co) and two samples (NS 6362-08, colourless, and JER 5124-28, a pale-green) contained added manganese (labelled N-3 Mn). The N-3 Co and N-3 Mn group averages for all elements are given in Appendix I. The samples of N-3 Co had cobalt added in quantities of around 400-750ppm (av. 589ppm). In N-3 Mn, manganese oxide

was present in amounts of 1.4% and 0.9% in each respectively. The latter quantity appears either insufficient or the furnace conditions inappropriate, to de-colourise the glass completely, nonetheless these quantities are high enough to suggest deliberate addition. Each of these additives also had associated elements, which can potentially provide clues as to the type of additive or their possible source. As the base glass for these samples is known, an opportunity presents itself for such additives to be investigated further. However, for an accurate comparison "fresh" glass without any colourant contamination from recycling should be used for this comparison. A "fresh" base glass for N-3 is calculated in Section 6.6 below, and is here denoted as N-3F. This data is used in the subsequent comparison and is included for reference in Appendix I, and used in Table 6.5.

6.5.1 The Cobalt Glass – N-3 Co

Comparisons between N-3 Co and N-3F found a number of elemental differences, of which 14 oxides demonstrated significant or near significant increases (Table 6.5; Figure 6.14). In this case, significance was recognised if the difference between the fresh and coloured glass was greater than 3 times the standard deviation (3σ). This would rule out differences due to variation in the base glass, and would suggest association with the colourant. Table 6.7 contains the oxides which show differences from the base glass, the first selection of elements showed differences greater than 3σ, illustrating large significant differences, and the remaining elements have differences between 1σ and 3σ, and indicate elements with differences of lesser or borderline significance, and which might be normal variation in the base glass.

The cobalt blue glasses contain significant differences in the oxides of: iron, which is 0.3-0.5% above the N-3F mean; lead (82-532ppm); copper (804-1252ppm); and zinc (368-1089ppm). Of these only ZnO showed a positive correlation with CoO (r^2=0.88; Figure 6.15a). Small but significant increases are also apparent in NiO (13-17ppm) and GaO (6-7ppm), with both of these exhibiting a correlation with CoO (r^2>9.8). TIB 5583-06 displayed consistently lower amounts of all oxides except zinc despite having the

Table 6.5. Selected oxides from the coloured samples (N-3 Co and N-3 Mn) which have indicated differences from the base glass (N-3F, the 'fresh' Egypt II glass, Table 6.6). On the left-hand side in green are oxides showing differences from the base glass at greater than 3 σ of N-3F. On the right-hand side, in orange, are the oxides which show lesser differences of between 1 σ and 3 σ. The complete data for the N-3 Co and N-3 Mn groups in comparison to N-3F is presented in Appendix I. Wt% and ppm as shown.

		> 3σ differences to the base glass								Between 1 σ and 3 σ difference to the base glass					
Group		**MnO**	**Fe_2O_3**	**PbO**	**CoO**	**CuO**	**ZnO**	**NiO**	**GaO**	**MgO**	**Al_2O_3**	**P_2O_5**	**K_2O**	**SrO**	**BaO**
N-3F	**Mean**	**0.02**	**0.93**	**4.08**	**3.2**	**3.1**	**17.9**	**7.4**	**3.7**	**0.53**	**2.56**	**0.09**	**0.26**	**203**	**173**
	1 σ	*0.003*	*0.087*	*1.7*	*0.9*	*1.13*	*2.6*	*1.1*	*0.4*	*0.084*	*0.195*	*0.016*	*0.063*	*15.8*	*12.8*
	3 σ	*0.01*	*0.26*	*5.2*	*2.7*	*3.4*	*7.7*	*3.3*	*1.2*	*0.25*	*0.58*	*0.05*	*0.19*	*47.5*	*38.5*
N-3 Co	**RAM 3592 03**	0.32	1.53	532	437	1252	368	13.4	6.2	0.75	2.73	0.13	0.41	247	226
	RAM 6297 06	0.34	1.45	92	589	960	618	16.2	6.6	0.73	2.71	0.1	0.4	229	210
	TIB 5583 06	0.23	1.28	82	742	804	1089	17.5	7.1	0.53	2.54	0.11	0.31	207	180
N-3 Mn	**NS 6362 08**	1.44	1.09	56.7	10.7	33.7	102	11.9	4.7	0.58	2.41	0.11	0.36	215	298
	JER 5124 28	0.91	0.94	14	5.5	15	59	9.7	4.1	0.57	2.25	0.09	0.3	218	243
		wt %		ppm						wt %				ppm	

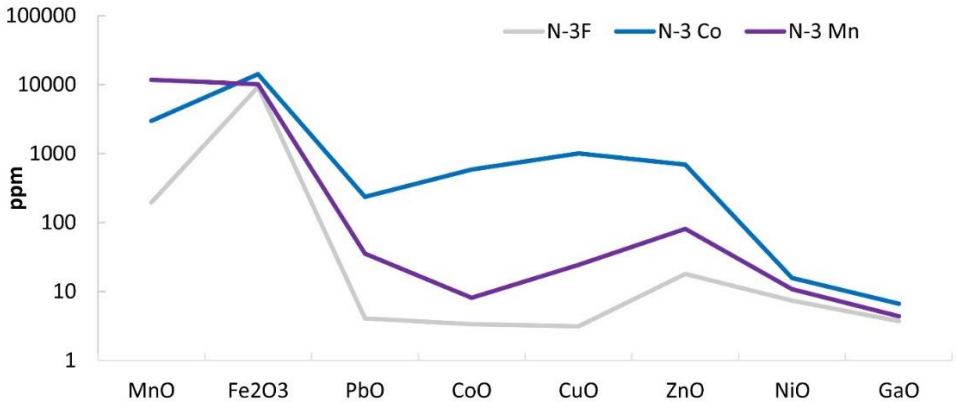


Figure 6.14. Line graph comparing the N-3 Co and N-3 Mn groups against N-3F (Egypt II 'Fresh' glass) using the oxides that showed differences >3σ as presented in Table 6.7. y-axis ppm log scale.

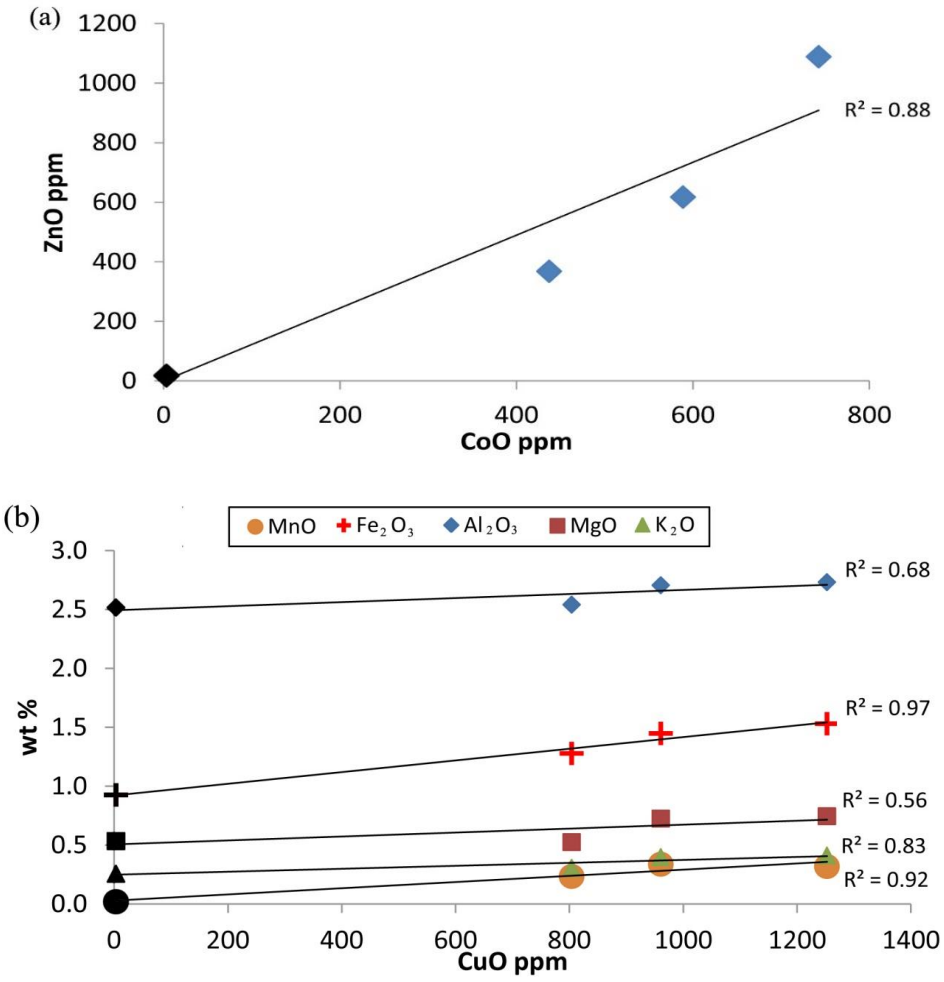


Figure 6.15 a) Image showing a positive correlation between ZnO and CoO in N-3Co. b) CuO against the oxides of Fe, Mn, Al, Mg and K for N-3 Co demonstrating positive correlations between these oxides. In all cases the black symbol is the N-3F value.

largest quantity of cobalt. It is also noted that RAM 3592-03 has a large lead content, this could represent contamination rather than from the ore source alone. The dissimilarity between TIB 5584-06 and the other two samples could denote a separate cobalt source, or it may also signify an inherent heterogeneity in the ore source. Furthermore, it may also indicate that the oxides which do not correlate with CoO may have entered via a separate glass component.

Increases in six further oxides are also identified of borderline significance; approximately 0.25% increases in MgO, Al_2O_3 and K_2O, and smaller amounts of P_2O_5, and between 5-50ppm increases in SrO and BaO. Note, however, that the MgO, K_2O and P_2O_5 could have entered through re-melting or recycling, rather than with the additive. Again, none of these exhibited a correlation with Co content, and TIB 5583-06 tended to show the smallest quantities. Of the oxides stated, Mn and Fe had the highest correlation with Cu (R^2=>0.9), and lesser associations are seen against the oxides of Al, Mg, K, Ba and Sr (R^2=0.6 to 0.88; Figure 6.15b). This result could suggest that two products were being added, a copper compound bearing iron and manganese (and possibly smaller amounts of Sr and Ba) and a cobalt compound bearing zinc. Shortland and Ermin (2006) also found elevated levels of copper in cobalt coloured Late Bronze Age glass, and suggested that this was possibly added to enhance the colour of the samples through the addition of copper where cobalt levels were low (ibid, 591). Another possibility is that the cobalt source employed was itself a combination of two different mineral mixes, a group in which Zn and Co are correlated, and a group in which the Cu, Fe, Mn, and possibly Al, Mg, K, Sr and Ba are correlated. This is possibly the more likely scenario. It must, however, be noted this is just three samples and more are required before conclusions can be reached.

Using the 8 elements with differences larger than 3σ presented in Table 6.5, and taking the N-3 Co average data (Appendix I) away from N-3F provides values which can be used to calculate an estimated average additive mix, consisting of of 48% Fe_2O_3, 27% MnO, 10% CuO, 7% ZnO, 6% CoO, 2% PbO and <0.1% NiO and GaO. This might suggest a mineral like asbolane, a cobalt mineral that also contains manganese (Kaczmarczyk and Hedges 1983, 53). Other oxides might also be included, such as flux oxides and alumina, however, their presence may be a result of sample variation or other

contamination such as fuel ash, rather than in the ore. There is substantial body of work regarding the origins of the cobalt pigments, much of which has focuses on Bronze Age Egyptian and Mesopotamian objects. Further comparisons with a larger data set including the plant ash glasses is made in Chapter 7.

6.5.2 The Manganese Glass – N-3 Mn

The additive used for the manganese oxide is cleaner than the cobalt source and contained fewer associated elements. Along with the manganese, the only associated oxide present in large quantities is barium, which increases by approximately 70-130ppm in the manganese decoloured glass. Smaller increases are seen in PbO (10-50ppm), CoO (2-7pmm), CuO (10-30ppm) and ZnO (30-80ppm), NiO (2-4ppm) and GaO (~1ppm). They all show a positive correlation and so most likely enter with the manganese, but with only two samples, not much more can be revealed and some of these increases may well be due to recycling. There is also a marginal increase in SrO (10-15ppm), however, it is within 1σ of the N-3F value and does not show a positive correlation with MnO, and is probably extraneous to the manganese. However, the increase in barium is a typical occurrence and recognised in association with manganese by other studies (Brill 1988; Jackson 2005; Silvestri 2008). Manganese oxide in the form of pyrolusite is considered to be a common, impurity free, mineral and so provenancing this raw material is unlikely to be possible. It is also noted that the additional manganese slightly increased to the LREE/HREE ratio. Further discussion of manganese with a larger sample range is presented in Chapter 7.

6.6 Recycling

Recycling was a commonplace occurrence and is been recognised from a number of glass assemblages (Freestone et al 2002A; 2008B; Freestone et al 2015; Schibille and Freestone 2016; Rehren et al 2010; Degryse et al 2006; Al-Bashaireh et al 2016) and is particularly prevalent in Roman glass (Foster and Jackson 2009, 196; Jackson and

Paynter 2016). Being able to recognise recycling is archaeologically important as it allows the estimation of the percentages of fresh glass in circulation. This would provide insights into the operation of the industry, as well as trade and economic activity. It is also important to understand and recognise recycling, as the act of recycling itself can blur compositional groups, muddying the provenance signature of a glass. This section will aim to identify the base or geological level of known colourant elements in the vessels, thereby facilitating the identification of fresh glass, which enables the recycled quantities to be estimated and averages for the fresh glass to be calculated, and allow examination of other recycling related contaminants to be performed.

What is meant by recycling? The definition of recycling applied here includes complete melting of vessels for reuse, but also the addition of cullet to fresh glass. The latter process is likely to be the most frequent way in which glass is reused. Therefore, the end product is not wholly recycled material, but in most cases a combination of fresh and recycled glass.

6.6.1 Characterising Recycled Glass

Figure 6.16 (a-d) presents the frequency of vessel for different abundances of four colourant oxides (Cu, Co, Pb, Mn) for groups N-1, N-2 and N-3 (N-4 omitted as too few samples are present). The geological level is expected to be low and to have a relatively small spread of values, this would be exhibited in the fresh glass. It would be recognised as the first high frequency spike, after which larger amounts, likely spread over a larger range, would be due to contamination via recycling. This is demonstrated clearly in the CoO and MnO graphs (Figure 6.16 a & d), where frequency spikes are seen in the 1.1-2.0ppm (N-1 and N-2) and the 3.1-4.0ppm (N-3) ranges for CoO. This suggests a geological level of <5ppm CoO for all three groups, although this number is slightly lower for N-1 and N-2. For MnO, all three glass groups show a frequency spike at the 110-200ppm range, which quickly reduces after 300ppm, giving an approximate geological level of below 400ppm. For N-3 a relatively clear cut-off is also demonstrated with PbO (9.1-10ppm) and CuO (8.1-9.0ppm CuO) as presented in Figure

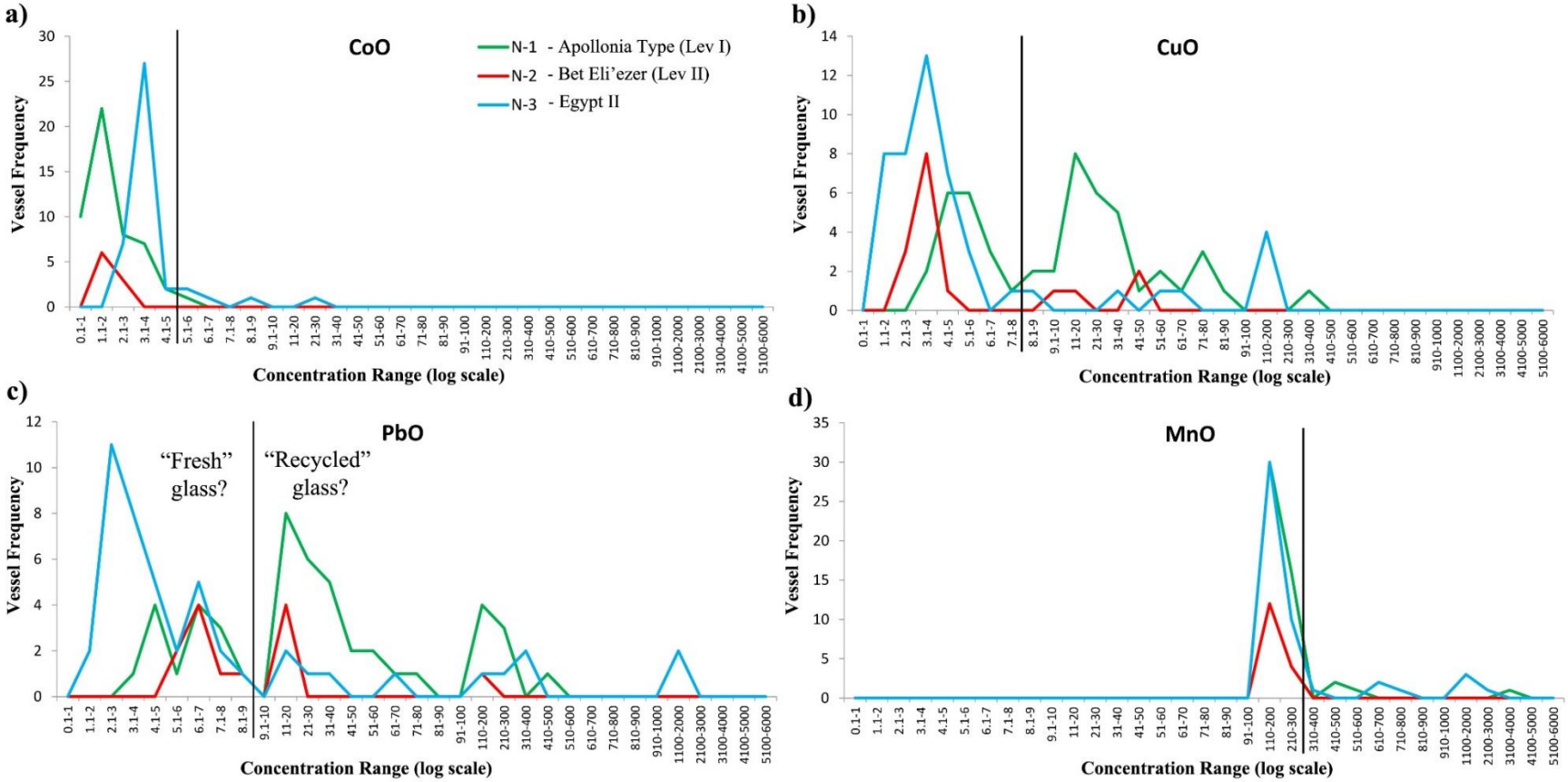


Figure 6.16. Investigation of the effects of recycling. Line diagrams present colourant oxide concentration against frequency of vessel for N-1, N-2 and N-3 (N-4 had too few vessels) for oxides of: a) cobalt; b) copper; c) lead; and d) manganese. These diagrams allow the estimation of geological levels of colourant, above this level recycling is implied. Suggested levels for fresh and recycled glass is indicated by a black line which differs for each oxide. The fresh and recycled sides are labelled in c). Concentrations ranges are in log scale as ppm.

6.16 b & c, with recycling suggested at levels above this. For the N-1 and N-2 groups large frequency spikes are seen in the 6.1-7.0ppm range for PbO, matching the N-3 group; and further peaks are apparent in the 11-50ppm range. The first peak denotes the geological level, and the second likely indicates the most frequent recycling level. N-1 and N-2 have a large number of vessels in the higher ranges which suggests that recycling is more prevalent in these groups. Similarly, CuO has a large frequency peak in the 3.1-8.0ppm range and a further spike in the 11-50ppm range, again suggesting a sizeable quantity of recycled glass. From these graphs, recycling is suggested at levels of >5 for CoO; >8 for CuO; >9 for PbO and >300 for MnO. The geological base levels identified here are generally consistent with sands analysed from the northern Mediterranean (Brems and Degryse 2014) which demonstrated transition metal contents of 100-1100ppm MnO, 1.54-4.5ppm Co, and Cu reported as being <30 to <76ppm. No data for Pb was provided. Similar MnO amounts in recycled glass (above 250ppm) are reported by Schibille et al (2016).

Using the criteria identified above the three compositional groups were each divided into “fresh” (denoted by a F) and “recycled” (R). As previously stated, the definition of recycling used here includes the addition of cullet to fresh glass, even if this is only in small quantities. The means for these groups are presented in Tables 6.6 (major and minor oxides), 6.7 (trace oxides) and 6.8 (REE oxides). It is important to be mindful that these groupings are guides only and do not account for potential anomalous variations in the sand or circumstances where recycling has avoided contamination. Calculating the percentages of recycled glass for each group indicated 72% of the N-1 glass vessels as possibly recycled, 53% of the N-2 glass and 33% of N-3 glass. The spatial and chronological distributions of the recycling glass, as well as the likely association with the wider industry are discussed in Chapters 8 and 9.

6.6.2 Investigation of the Recycled Glass

Comparing the differences between the fresh and recycled glass indicates some notable differences. Firstly, overall, the variance in oxides of fresh glass is smaller than the recycled glass. A wider variance in the recycled glass is to be expected, as the batch

Table 6.6. Mean values for the major, minor and selected trace oxides for the "fresh" and "recycled" glass for groups N-1, N-2 and N-3. Fresh glass is denoted by F and recycled by R. Values as wt % unless otherwise specified.

Group	N		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO‡	SrO‡	ZrO_2‡	BaO	Total Col*
N-1F	15	**M**	**14.43**	**0.52**	**3.18**	**72.07**	**0.06**	**0.83**	**0.54**	**7.70**	**0.09**	**0.47**	**193**	**488**	**63**	**259**	**206**
		S.D	*0.70*	*0.08*	*0.14*	*1.06*	*0.02*	*0.09*	*0.09*	*0.87*	*0.01*	*0.07*	*21*	*51*	*6*	*9*	
N-1R	39	**M**	**14.26**	**0.58**	**3.16**	**71.04**	**0.11**	**0.83**	**0.66**	**8.63**	**0.08**	**0.48**	**309**	**502**	**59**	**256**	**419**
		S.D	*1.04*	*0.08*	*0.20*	*1.57*	*0.05*	*0.09*	*0.18*	*1.20*	*0.01*	*0.07*	*511*	*47*	*8*	*24*	
N-2F	8	**M**	**12.42**	**0.50**	**3.21**	**74.84**	**0.08**	**0.73**	**0.57**	**7.02**	**0.08**	**0.43**	**183**	**456**	**57**	**249**	**194**
		S.D	*0.75*	*0.09*	*0.21*	*0.73*	*0.02*	*0.04*	*0.13*	*0.44*	*0.01*	*0.07*	*24*	*34*	*9*	*18*	
N-2R	9	**M**	**11.87**	**0.52**	**3.31**	**74.46**	**0.08**	**0.66**	**0.50**	**7.66**	**0.09**	**0.55**	**200**	**451**	**63**	**254**	**1828**
		S.D	*0.98*	*0.07*	*0.22*	*0.86*	*0.03*	*0.08*	*0.11*	*1.39*	*0.02*	*0.12*	*27*	*44*	*12*	*19*	
N-3F	37	**M**	**14.08**	**0.53**	**2.52**	**70.60**	**0.09**	**1.06**	**0.26**	**9.55**	**0.26**	**0.93**	**195**	**203**	**239**	**173**	**206**
		S.D	*0.83*	*0.08*	*0.19*	*0.92*	*0.02*	*0.07*	*0.06*	*0.67*	*0.03*	*0.09*	*29*	*16*	*41*	*13*	
N-3R	13	**M**	**14.33**	**0.70**	**2.56**	**70.13**	**0.13**	**0.95**	**0.40**	**9.41**	**0.24**	**0.91**	**826**	**261**	**223**	**180**	**1233**
		S.D	*1.82*	*0.35*	*0.38*	*1.22*	*0.05*	*0.14*	*0.22*	*1.26*	*0.05*	*0.13*	*808*	*84*	*59*	*30*	

‡ MnO, SrO and ZrO2 as ppm; * Total Colourants = MnO+CoO+CuO+PbO (ppm)

Table 6.7. Mean trace oxides for the fresh and recycled glass groups. Values as ppm.

Group		B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	Nb_2O_3	MoO	Ag	SnO_2	Sb_2O_3	HfO_2	Ta_2O_3	WO	PbO	ThO_2	UO_2
N-1F	**M**	**163**	**16.6**	**40**	**1.7**	**5.0**	**5.2**	**9.7**	**4.2**	**1.9**	**10.2**	**2.2**	**0.4**	**bdl**	**3.1**	**bdl**	**1.3**	**0.1**	**0.1**	**6**	**1.1**	**1.1**
	S.D	*32*	*2.3*	*43*	*0.4*	*0.9*	*1.0*	*3.2*	*0.4*	*0.3*	*1.6*	*0.3*	*0.1*	bdl	*4.9*	*bdl*	*0.1*	*0.0*	*0.0*	*1*	*0.1*	*0.5*
N-1R	**M**	**223**	**17.3**	**34**	**2.2**	**5.5**	**35.4**	**14.6**	**4.1**	**3.7**	**10.4**	**2.0**	**0.4**	**0.06**	**11.3**	**bdl**	**1.3**	**0.1**	**0.1**	**73**	**1.0**	**1.1**
	S.D	*67*	*3.1*	*29*	*1.3*	*1.3*	*54.5*	*7.3*	*0.5*	*6.9*	*1.7*	*0.3*	*0.2*	0.07	*16.7*	*bdl*	*0.2*	*0.0*	*0.0*	*96*	*0.1*	*0.4*
N-2F	**M**	**168**	**14.8**	**50**	**1.7**	**4.5**	**3.3**	**8.2**	**3.9**	**1.8**	**10.5**	**2.0**	**0.3**	**bdl**	**6.6**	**bdl**	**1.2**	**0.1**	**0.1**	**6**	**1.0**	**0.7**
	S.D	*39*	*2.3*	*57*	*0.1*	*0.7*	*0.7*	*1.3*	*0.4*	*0.3*	*1.7*	*0.3*	*0.1*	bdl	*6.1*	*bdl*	*0.2*	*0.0*	*0.0*	*1*	*0.1*	*0.1*
N-2R	**M**	**152**	**18.0**	**38**	**1.9**	**5.7**	**14.7**	**11.2**	**4.2**	**1.8**	**9.0**	**2.3**	**0.4**	**0.19**	**18.6**	**bdl**	**1.3**	**0.1**	**0.1**	**1611**	**1.1**	**0.8**
	S.D	*37*	*2.4*	*43*	*0.8*	*1.0*	*16.6*	*3.9*	*0.6*	*0.7*	*1.3*	*0.4*	*0.1*	0.33	*29.6*	*bdl*	*0.2*	*0.0*	*0.0*	*3147*	*0.2*	*0.1*
N-3F	**M**	**264**	**36.1**	**53**	**3.3**	**7.4**	**3.1**	**17.9**	**3.7**	**1.9**	**4.7**	**4.6**	**0.1**	**0.07**	**8.0**	**bdl**	**5.0**	**0.2**	**0.1**	**4**	**1.8**	**1.1**
	S.D	*73*	*4.3*	*39*	*0.5*	*1.1*	*1.1*	*2.6*	*0.4*	*1.2*	*0.9*	*0.4*	*0.1*	0.06	*6.7*	*bdl*	*0.8*	*0.0*	*0.0*	*2*	*0.2*	*0.2*
N-3R	**M**	**288**	**34.5**	**42**	**5.4**	**8.4**	**60.1**	**36.5**	**3.5**	**3.5**	**5.8**	**4.3**	**0.4**	**0.22**	**32.1**	**14.0**	**4.9**	**0.2**	**0.1**	**342**	**1.8**	**1.2**
	S.D	*57*	*5.8*	*9*	*2.8*	*1.7*	*65.0*	*25.0*	*0.4*	*1.9*	*1.6*	*0.7*	*0.2*	0.16	*30.2*	*26.8*	*1.4*	*0.0*	*0.1*	*489*	*0.3*	*0.2*

Table 6.8. Mean REE oxides for the fresh and recycled glass groups. Values as ppm.

Group		Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu Anom	La/Yb	Total REE
N-1F	**M**	**9.18**	**8.79**	**17.00**	**1.97**	**7.63**	**1.51**	**0.45**	**1.25**	**0.22**	**1.28**	**0.28**	**0.73**	**0.10**	**0.66**	**0.10**	0.32	13.39	51.1
	S.D	*0.57*	*0.65*	*1.61*	*0.14*	*0.47*	*0.11*	*0.04*	*0.10*	*0.02*	*0.11*	*0.02*	*0.06*	*0.01*	*0.05*	*0.01*			
N-1R	**M**	**9.01**	**8.19**	**15.63**	**1.89**	**7.51**	**1.50**	**0.42**	**1.30**	**0.22**	**1.30**	**0.28**	**0.74**	**0.10**	**0.69**	**0.10**	0.30	11.90	48.9
	S.D	*0.73*	*0.74*	*1.50*	*0.12*	*0.48*	*0.12*	*0.06*	*0.14*	*0.02*	*0.11*	*0.02*	*0.07*	*0.01*	*0.05*	*0.01*			
N-2F	**M**	**8.42**	**7.95**	**15.18**	**1.81**	**7.23**	**1.47**	**0.41**	**1.26**	**0.20**	**1.24**	**0.26**	**0.69**	**0.10**	**0.66**	**0.10**	0.30	12.07	47.0
	S.D	*0.44*	*0.72*	*1.54*	*0.13*	*0.47*	*0.13*	*0.05*	*0.13*	*0.02*	*0.07*	*0.02*	*0.05*	*0.01*	*0.06*	*0.01*			
N-2R	**M**	**8.87**	**8.49**	**16.33**	**1.92**	**7.53**	**1.47**	**0.43**	**1.31**	**0.21**	**1.25**	**0.26**	**0.70**	**0.10**	**0.69**	**0.10**	0.31	12.23	49.7
	S.D	*0.91*	*0.99*	*1.88*	*0.16*	*0.59*	*0.11*	*0.07*	*0.11*	*0.02*	*0.12*	*0.02*	*0.06*	*0.01*	*0.05*	*0.01*			
N-3F	**M**	**8.29**	**8.37**	**16.20**	**1.98**	**7.63**	**1.53**	**0.37**	**1.31**	**0.21**	**1.29**	**0.27**	**0.77**	**0.12**	**0.85**	**0.13**	0.26	9.79	49.3
	S.D	*0.60*	*0.57*	*1.16*	*0.13*	*0.54*	*0.12*	*0.04*	*0.13*	*0.02*	*0.13*	*0.02*	*0.07*	*0.01*	*0.09*	*0.01*			
N-3R	**M**	**8.70**	**8.52**	**16.32**	**1.99**	**7.88**	**1.60**	**0.36**	**1.34**	**0.22**	**1.37**	**0.29**	**0.81**	**0.12**	**0.89**	**0.13**	0.25	9.61	50.6
	S.D	*0.77*	*0.60*	*1.06*	*0.16*	*0.75*	*0.14*	*0.05*	*0.18*	*0.02*	*0.14*	*0.02*	*0.09*	*0.01*	*0.11*	*0.02*			

would probably contain glass from a greater number of sources, for example, more than one production batch of the same composition, or additional compositional groups, and the additional of coloured glass attached as decoration. Secondly, as well as the colourant oxides already mentioned, contents of other transition metals, e.g. Fe_2O_3, NiO, ZnO, SnO, As_2O_3, are also raised and imparted into the glass. These elements are frequently associated with metal ores and enter with the colourants. Iron oxide might also result from contamination from the crucible or tank utilised for the re-melting (Jackson and Paynter 2016) or from the blow pipe (Freestone 2015, 30). A third group of elevated elements are the flux oxides: MgO, K_2O, P_2O_5, and CaO. These originate from the fuel ash. The more potash can be dissolved into the glass surface from the furnace atmosphere, while less volatile oxides (MgO, P_2O_5 and CaO) are deposited as ash onto the glass surface. Elevated levels of flux and their association with melting within a furnace has been demonstrated experimentally by Paynter (2008), and are also recognised in archaeological glasses (Rehren et al 2010; Jackson and Paynter 2016; Schibille et al 2016). It is reasoned that recycling increases the timeframe a glass is molten within a furnace, thereby increasing the time in which this type of contamination can occur. Therefore, it might be proposed that the levels of flux elements in a glass is proportional to the number of recycling events, or at least to the length of time a glass remains molten. Paynter (2008) was able to show experimentally that potash levels in a molten glass rose slowly over time (p280).

Figure 6.17a displays potash against phosphorus oxide for the fresh and recycled glass groups. The figure demonstrates a positive correlation between the oxides in N-1 (r^2=0.33) and N-3 (r^2=0.77), although this is not observed in the samples of N-2 (r^2=0.002). This suggests that P_2O_5 and K_2O enter the glass together. Furthermore, a link between recycling and elevated P_2O_5 and K_2O is also demonstrated, with the higher levels of these oxides tending to occur in the vessels identified as recycled. There are some exceptions to this, which may be due to misidentified recycled glass or instances where “fresh” glass has become contaminated with flux oxides, however, on the whole, association is evident between the recycled glass and higher flux levels.

This association is further investigated in Figure 6.17b, where phosphorus oxide is presented against the sum of selected transition metals (NiO, ZnO, As_2O_3, SnO, CuO,

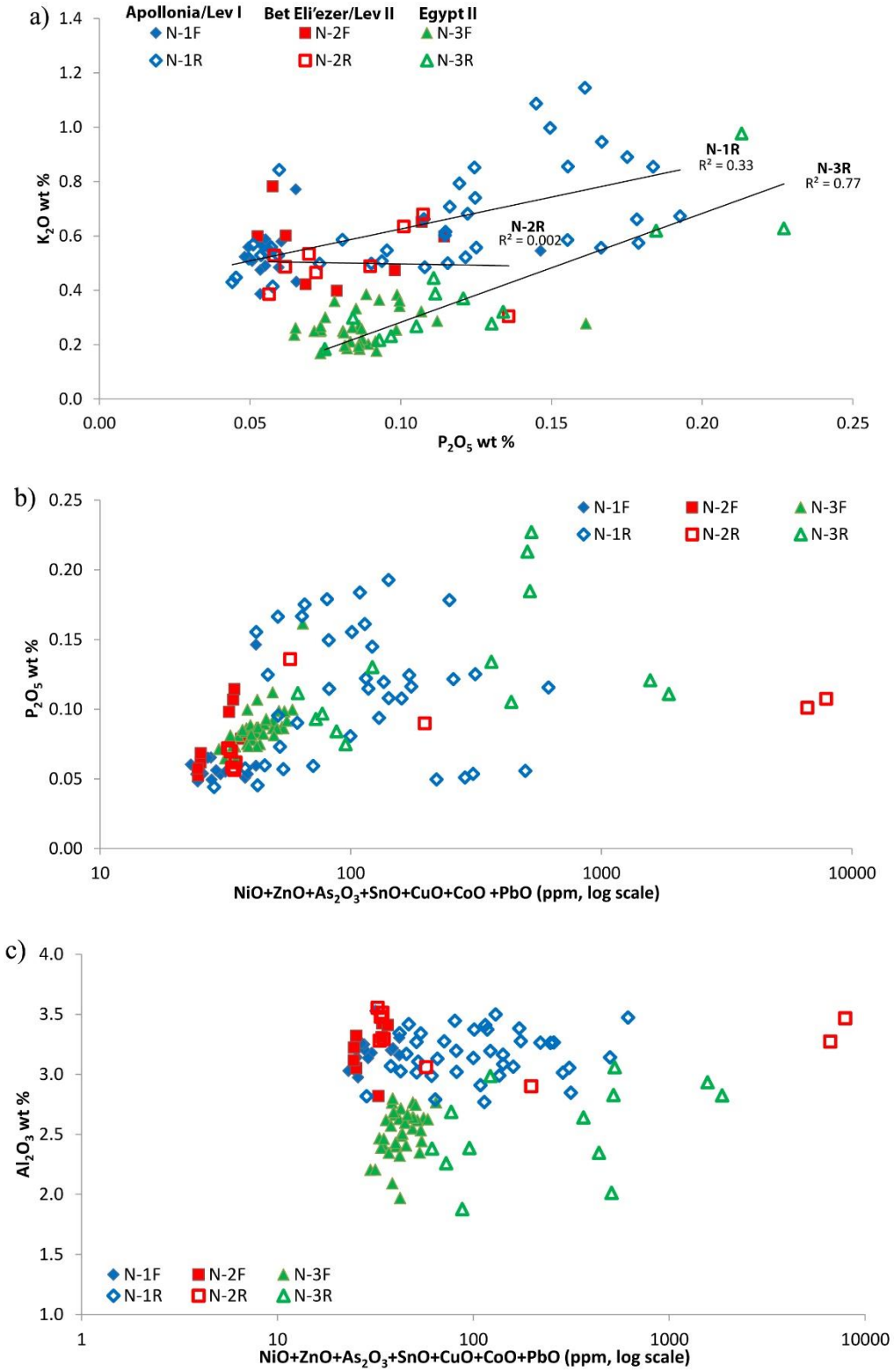


Figure 6.17. Graphs presenting the fresh (F) and recycled (R) glass groups to investigate the effects of recycling. a) Potash against phosphorous oxide, demonstrating positive correlations in the N-1R and N-3R groups. Trend lines and R^2 values for the recycled glass shown. b) Display of potash against the sum of selected colourant oxides, with some positive correlation shown. x-axis log scale, ppm. c) Alumina against the sum of selected colourant oxides to investigate furnace/crucible contamination. No overall correlation is seen. X-axis, log scale in ppm.

CoO and PbO). MnO was not included as it is present in much higher and more variable amounts than the other oxides. In theory, both flux and transition metals can act as proxies denoting the 'amount' of recycling. The more times a sample is recycled, the bigger the window in which contamination can occur, and therefore, the higher the potential phosphorus oxide level. Similarly, if each melted batch only contains a tiny fraction of transition metal contaminants, every subsequent recycling event would increase the content of a vessel. Figure 6.17b demonstrates that, for the vast majority of samples, it does appear that abundance of colourant oxides in a vessel increases with P_2O_5. The greatest degree of positive correlation is seen in samples with colourants lower than 200ppm. The correlation then seems to break down after this, likely because larger amounts of colourants are related to specific events where glasses with high colourant levels are added, such as the addition of mosaics.

This must be due to additions of glass with larger amounts of colourants. Potentially, samples with a high phosphorus oxide and a high transition metal oxide content can be identified as "more" recycled than vessels with lower amounts of both, as long as colourants contents are <200ppm. However, there are some exceptions. Some N-1R samples do not have raised levels of P_2O_5. Conversely, a small group of fresh glass, three samples of N-2F, have elevated P_2O_5. This may suggest contamination during the primary or secondary working stages without the mixing in of old glass (cullet).

Contamination from the melting chamber or crucible has been demonstrated in Roman glass (Jackson and Paynter 2016) with elevated levels of iron oxide, titania and alumina exhibited in glass thought to be recycled. It has already been noted that iron oxide is slightly raised in the recycled glass. Figure 6.17c compares levels of alumina against the summed total of transition metals, however there does not appear to be a link between recycling and alumina in most samples. There does, however, seem to be a slight increase in alumina of the N-3R group, but this might be explained by some of the N-3R samples being a mix of Egypt II and Levantine glass (see below). It is noted that the alumina content would be higher in crucibles rather than tank furnace lining, and as tank furnaces were most likely used in the melting of these vessels, a very limited effect on the alumina content would be expected here. There is also an effect due to the capacities of the different containers. The many tonnes of glass within a

tank furnace would have its alumina content increased very little compared to glass within a much smaller crucible. The ability of glass to mix thoroughly would also have an effect, with any contamination in the glass in a tank furnace concentrated nearest the furnace walls.

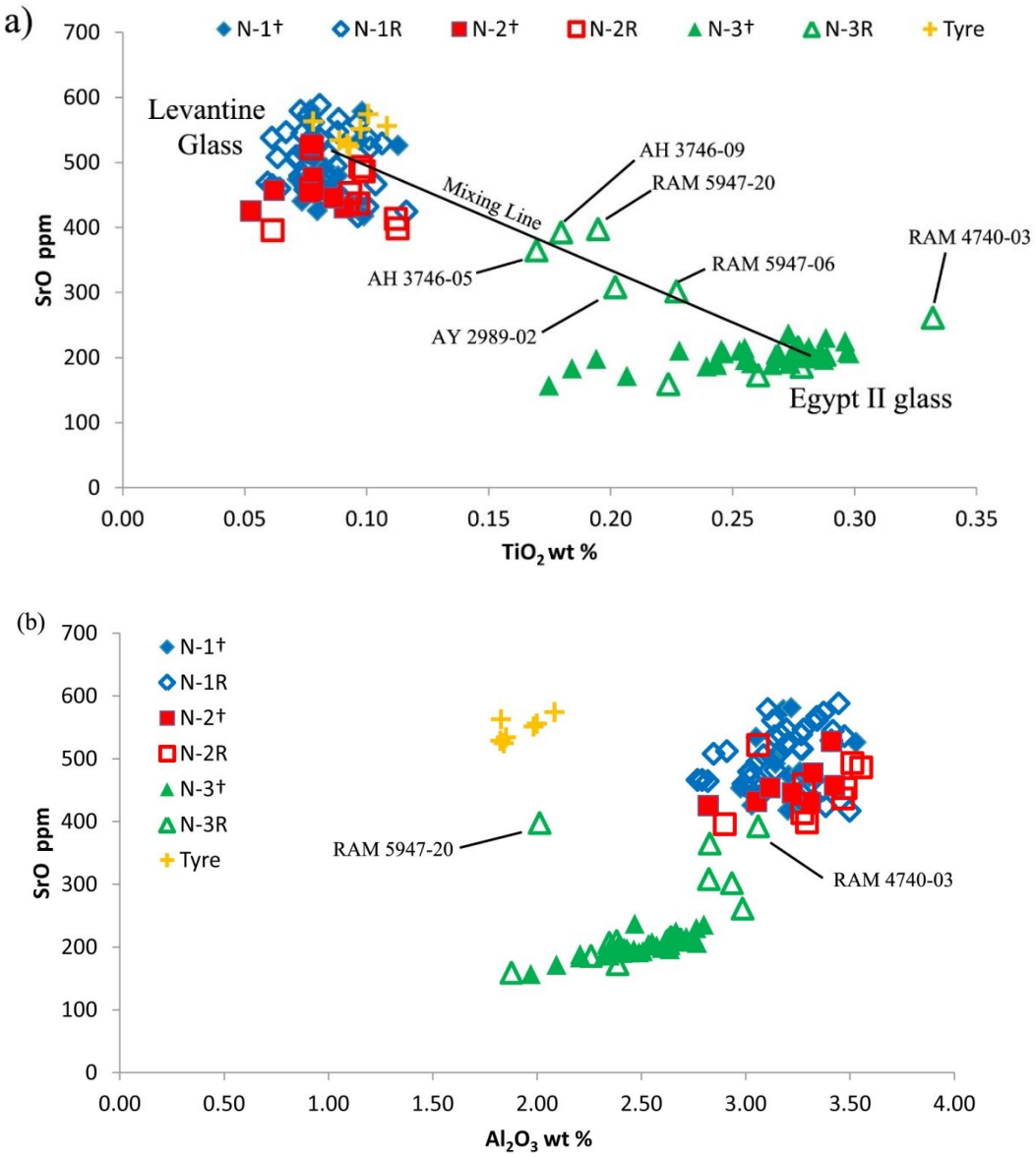


Figure 6.18. The relationship between the recycled glass and the main natron groups and the Tyre plant ash group. Fresh (F) and recycled (R) glass for N-1, N-2 and N-3 are presented alongside the plant ash glass from Tyre (Phelps and Freestone; data Appendix B). a) Graph is of SrO against TiO_2. A mixing line between the Levantine and Egyptian glass indicates the mixing of five samples of N-3R. b) Graph is of SrO and Al_2O_3 demonstrating that RAM 5947-20 is possibly a mix of Tyre and Egypt II glass, while the others (except RAM 4740-03) are mixes with Levantine natron glass.

Looking now to the individual glass groups, six samples of N-3R contain high amounts of SrO in the region of 260-500ppm, while the N-3F average is 203ppm (s.d 16ppm). To investigate this further, graphs of SrO against Al_2O_3 and SrO against TiO_2 were plotted for the fresh and recycled glass groups (Figures 6.18 a & b). In addition, the Tyre plant ash glass group was included for comparison (Appendix B). Groups N-1R and N-2R deviate very little compositionally from their base glass. This suggests intermixing within the Levantine groups rather than mixing with alternative groups. That said, three recycled samples do pull away from the Levantine main body and fall along a Levantine-Egyptian glass mixing line, although the dilution is only minimal. For the N-3R glass, only three samples indicate intermixing within the group and the majority demonstrate mixing with glass from outside the group. Five of the six high strontium oxide samples mentioned above form a mixing line between the Levantine (and Tyre) glass groups and the N-3F group. Note that one of these (RAM 5947-20) is a vessel with an intermediate flux content, as identified earlier in Figure 6.1. The sixth vessel, RAM 4740-03, contains elevated amounts of titania, indicating it to be mixed with an unknown glass type. Figure 6.18b separates the five mixed samples further, demonstrating that RAM 5947-20 is most likely a mix of N-3 and Tyre glass as it falls on a mixing line between these two groups. The Tyre glass is a plant ash type, and therefore demonstrates the mixing of natron and plant ash glass. This would explain the relatively high quantities of flux oxides in this glass. The remaining four vessels are amalgamations of Levantine glass and Egypt II. From their position along the mixing line, a mix of approximately of 50-80% Egypt II with lesser quantities of Levantine glass can be estimated. These results indicate that local Levantine glass, most likely as cullet, is being combined with Egyptian glass, and that much less Egyptian glass is being recycled with itself. This possibly suggests that cullet primarily consisted of Levantine glass types, inferring that this type was more prevalent in supply, which is expected as this type was locally produced. This is discussed further in Chapter 9.

Finally, some samples contain amounts of colourant elements above 1000ppm which might suggest deliberate addition. Two samples, JER 5124-18 and NS 6362-02, contain 6497 and 7769ppm PbO, potentially high enough to suggest deliberate addition. One sample is green and the other olive green, both colours uncommon to the N-2 group.

In group N-3R two samples (AY 2989-02 and RAM 5947-06) had PbO of 1554 and 1222ppm, and four samples (AH 3746-11; -05; -09 and RAM 5947-20) contained MnO ranging from 1107 to 2910ppm. These higher levels are more than is suggested from the other recycled glasses, and could, therefore, imply some deliberate addition, or it could simply be the mixing of glass with more strongly coloured samples, giving rise to increased colourant amounts.

6.7 The Outliers

During statistical analysis 8 samples were removed as outliers for having unique or intermediate compositions which did not readily belong within the four principal groups (outlier results in Appendix H). To investigate potential mixing, the outlier samples are presented in Figures 6.19 a & b, with some of the samples and the intermediate flux group vessels labelled. In Figure 6.19a all eight outliers fall on a mixing line between the Levantine and Egyptian glass groups. Figure 6.19b splits these vessels into two groups, the first are the vessels with an intermediate flux content (JER 3835-08, -10 and RAM 4740-11) which were first identified in Figure 6.1. They share a mixing line between the Tyre and Egypt II (N-3) glass types, showing them to be a combination of natron and plant ash glass. The second group consists of five samples (NS 6362-04, -10, RAM 5947-03, -22, AH 3746-03) which fall on a mixing line between the Levantine natron glass (N-1 and N-2) and the Egyptian glass, although the spread of the sample compositions is relatively wide. Note that two of the samples, AH 3746-03 and RAM 5947-22, differ slightly from the others, in that they both contain enhanced amounts of colourant elements, 3596 and 1735ppm MnO, 4484 and 3311ppm. Furthermore, AH 3746-03 is the only analysed sample to contain significant amounts of Sb_2O_5 (2116ppm). As antimony was used as an ingredient in glass by Roman glassmakers during the 1^{st}-3^{rd} centuries (Foster and Jackson 2010), it suggests this sample was at one stage mixed with a glass of Roman origin. The sample is an Umayyad bowl, dated through context and style (Figure 6.20) and is very unlikely to have been misdated, indicating the glass was recycled and reused.

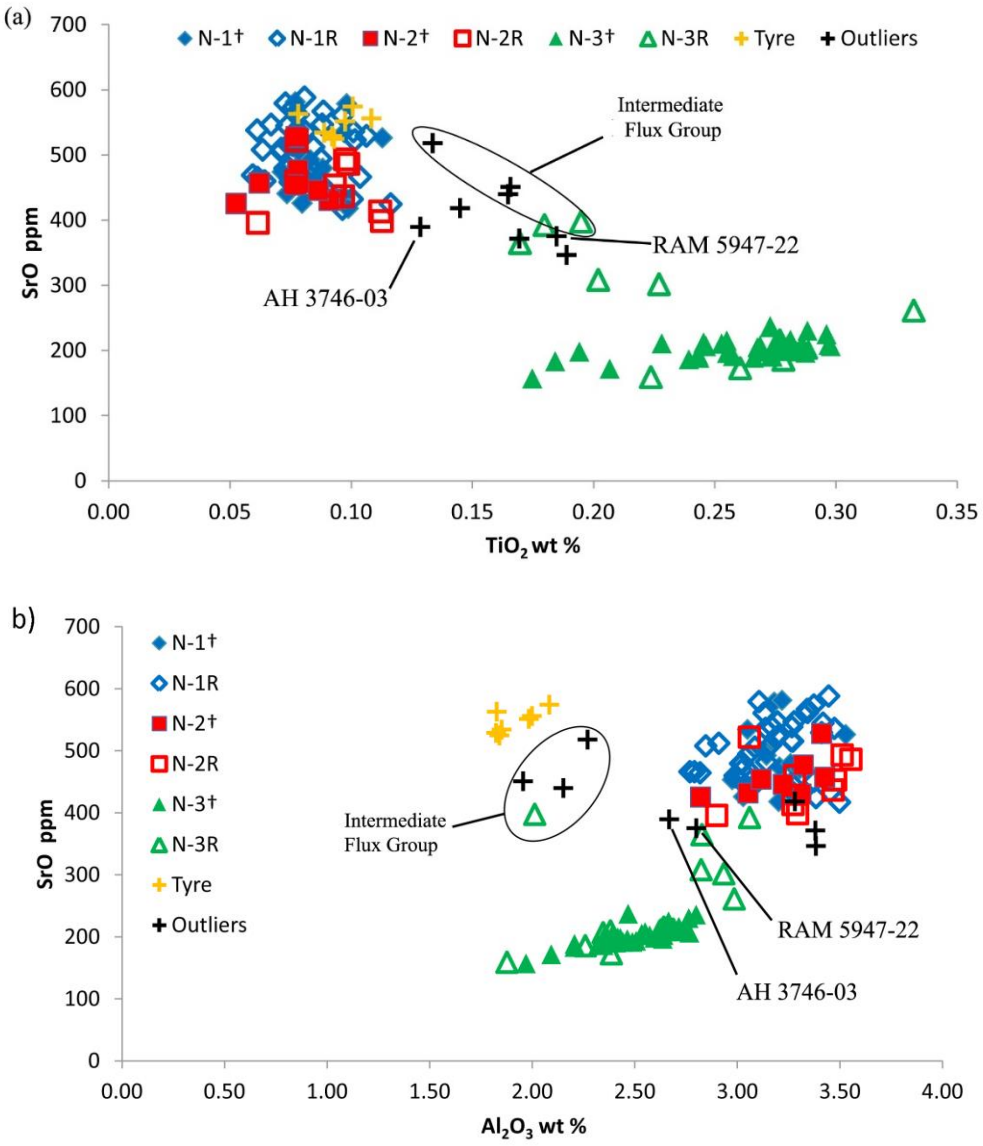


Figure 6.19. Graphs displaying the relationship of the 8 outlier samples against natron and Tyre glass groups. Selected samples and the intermediate flux samples are labelled. Images demonstrate mixing between the Egypt II and Levantine glass group in a) and between Egypt II and Tyre glass groups in b).

Figure 6.20. Photo and drawing of sample AH 3746-03. This is an Umayyad period vessel containing some antimony, suggesting a Roman origin to *some of the constituent glass.*

Chapter 7

Results: Plant Ash Glass

7.1 Plant Ash Glass Groups

7.1.1 Group Identification

This section reports the results for the 151 vessels identified as plant ash glass in Chapter 6 (Figure 6.1). The vessels were separated into compositional groups using Hierarchical Cluster Analysis (HCA). After exploratory investigations, six oxides were chosen to produce the finalised HCA diagram presented in Figure 7.1: three oxides that are considered to principally derive from the plant ash (P_2O_5, CaO and MgO) and three which mainly derive from the silica source (Al_2O_3, Fe_2O_3 and ZrO_2). These oxides are affected by raw material choice (i.e. source of flux, type of sand, but also the addition of cobalt for the iron), recipe (flux:sand mix) but also, potentially, by technology (plant processing). Comparisons using a broader range of elements are presented below but for the finalised HCA a confined range of elements were selected as they were able to produce the most consistent set of groupings. For example, trace oxides are neglected at this stage for two reasons: i) the Relative Standard Deviations (R.S.D.) of trace oxides tend to be high, leading to greater skews within the data, consequently leading to the fragmentation of clusters and the generation of more outliers; and ii) trace elements are useful in defining the geochemistry of a sediment, however in regions where the geological inputs are similar, separation between production groups is less likely to be achieved by conservative elements, such as the rare earths, and more likely achieved by the relative amounts of accessory minerals (e.g. feldspars, zircons, rutile, iron oxides) which can be proxied by a relatively restricted range of elements such as Al, Fe and Zr. Furthermore, some major and minor elements were also neglected; K_2O could

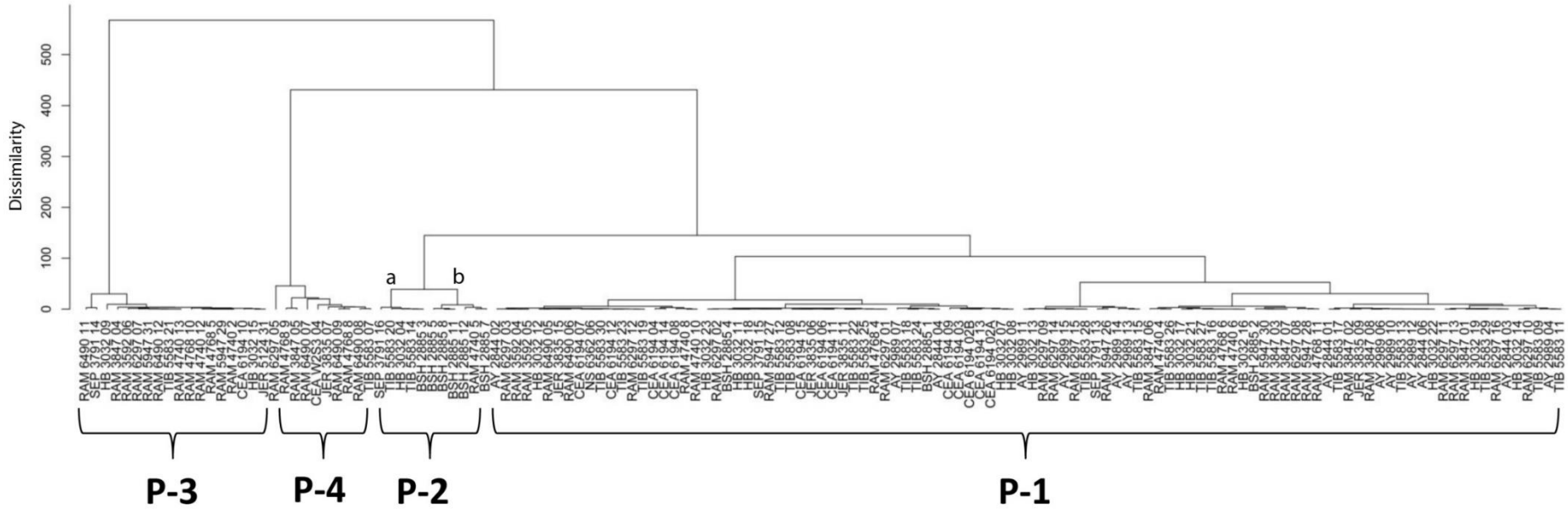


Figure 7.1. Hierachical cluster analysis (Wards's method) with the four principal plant ash groups labelled. The separation of P-2 into (a) and (b) branches is also shown. The oxides used are Al_2O_3, MgO, CaO, Fe_2O_3, P_2O_5 and ZrO_2. Nine samples are removed as outliers and can be found in the outlier section of Appendix J. N= 142.

not be used due to the strong overlap between the samples, this reduced group separation. TiO_2 was also avoided for two reasons: i) it correlated strongly with ZrO_2, which is not beneficial in HCA and should be minimised (see Baxter 2001, 690); and ii) that the large TiO_2 range within one particular group, due to natural variation in the sand, caused it to split artificially into two groups. Not using TiO_2 prevented this.

The finalised HCA, presented in Figure 7.1, identified four principal groups. The first branches at an approximate dissimilarity of 550 to form P-3, the second at just over dissimilarity 400 to form P-4. The final two groups branch at around dissimilarity 150. The largest of these, P-1, falls to the right and a smaller but closely related group, P-2, falls to the left. There is an additional much smaller branch within P-2 at around dissimilarity 40, these two branches are labelled (a) and (b), and their validity is discussed later. Within P-1 there is further branching identifiable at around dissimilarity 100, however, investigation (see below) found no justification for these sub-grouping using additional elements or through comparison with contextual information.

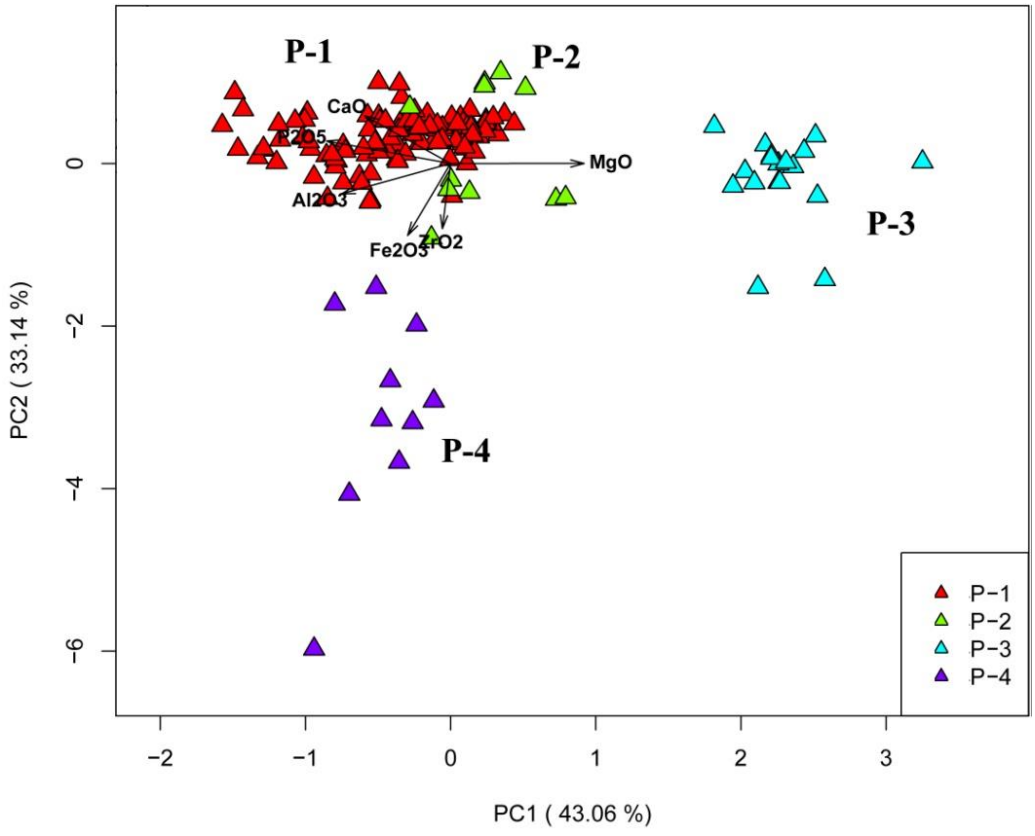


Figure 7.2. PCA bi-plot of the plant ash glass using principal components 1 and 2. Groups labelled and oxides used as in Figure 7.1. N=142.

A Principal Component Analysis (PCA) bi-plot in Figure 7.2 demonstrates the oxide weightings for the four identified groups. Principal Components (PC) 1 and 2 were used as these describe the highest amount of variation (PC1 43.1% and PC2 33.1%) and present the best separation. (Details of PCA process can be found in Chapters 5 and 6). PC1 separates P-1 and P-2 to the top left of the image, these are characterised by high quantities of P_2O_5, CaO and Al_2O_3. P-3 falls to the right, characterised by high concentrations of MgO. In the vertical direction, PC2 separates P-4 from the other groupings using Fe_2O_3 and ZrO_2. P-1 and P-2 do not separate due to similarities within mainly the flux oxides, however, some differences are observable in the silica related oxides (ZrO_2, Al_2O_3) which act to position samples of P-2 above, below and slightly to the right of the main P-1 cluster. This diagram also highlights the division within the P-2 group with five samples (termed P-2a) to the top of the P-1 group and six samples (P-2b) just to the bottom of the P-1 group. Mean and standard deviations for the identified groups are shown in Table 7.1 for major, minor and selected trace oxides; Table 7.2 for trace oxides and Table 7.3 for REE oxides. The individual sample data is presented in Appendix J sorted by compositional group.

During statistical analysis, nine outliers were identified (see outlier category of Appendix J). These samples had unique or intermediate compositions which did not fit into the emerging groups and were removed from the HCA. These samples most likely present recycled or minor production types, and are discussed in Section 7.3.

Table 7.1. Major, minor and selected trace oxides for the four plant ash groups identified in Figure 7.1. Weight % unless otherwise noted. Flux ratios also shown. M = Mean. S.d. = Standard Deviation.

Group	Type	No.	Colour*		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO	CoO†	SrO†	ZrO_2†	MgO/CaO	K_2O/P_2O_5
P-1	Tyre Type	102	colourless	**M**	**12.38**	**3.02**	**1.86**	**67.92**	**0.30**	**0.77**	**2.53**	**9.48**	**0.08**	**0.50**	**1.00**	**48**	**673**	**48**	**0.32**	**8.41**
				S.D	*1.07*	*0.51*	*0.20*	*1.69*	*0.06*	*0.11*	*0.35*	*1.17*	*0.02*	*0.12*	*0.38*	*49*	*131*	*7*		
P-2	Unknown Syro-Palestine Type	11	pale bluish green	**M**	**12.55**	**3.35**	**0.90**	**69.29**	**0.33**	**0.75**	**2.25**	**9.49**	**0.09**	**0.42**	**0.43**	**88**	**598**	**108**	**0.35**	**6.80**
				S.D	*1.85*	*0.32*	*0.12*	*2.11*	*0.05*	*0.10*	*0.30*	*0.99*	*0.02*	*0.07*	*0.42*	*77*	*100*	*53*		
P-3	Nishapur Colourless Type	18	colourless	**M**	**12.41**	**5.09**	**1.01**	**71.36**	**0.10**	**0.61**	**2.48**	**6.06**	**0.04**	**0.29**	**0.44**	**20**	**449**	**57**	**0.84**	**24.66**
				S.D	*1.34*	*0.50*	*0.18*	*1.68*	*0.02*	*0.08*	*0.41*	*0.81*	*0.01*	*0.09*	*0.20*	*41*	*45*	*35*		
P-4	Nishapur Coloured Type	10	Cobalt blue	**M**	**13.05**	**2.94**	**2.37**	**67.28**	**0.21**	**0.72**	**2.03**	**6.80**	**0.14**	**2.39**	**1.25**	**3987**	**481**	**142**	**0.43**	**9.68**
				S.D	*1.05*	*0.43*	*0.43*	*1.54*	*0.03*	*0.07*	*0.50*	*1.26*	*0.03*	*0.65*	*0.54*	*1665*	*131*	*62*		

Colour* = Most frequent colour; † = reported as ppm

Table 7.2. Trace oxides for the four plant ash groups. Concentrations in ppm. Li_2O, Au, Cd, Sb_2O_5, Pt, In, Se and Bi are removed as 1 or more results was below the detection limit.

Group	B_2O_3	V_2O_5	Cr_2O_3	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Nb_2O_3	MoO	Ag	Cd	SnO_2	Cs_2O	BaO	HfO_2	Ta_2O_3	WO	PbO	ThO_2	UO_2
P-1	**258**	**22**	**20**	**10.3**	**48**	**40**	**3.55**	**3.1**	**16.7**	**673**	**2.0**	**3.0**	**0.14**	**bdl**	**4.6**	**0.13**	**282**	**1.06**	**0.10**	**0.27**	**29**	**0.96**	**0.51**
	33	*5*	*16*	*2.0*	*49*	*11*	*0.54*	*0.9*	*2.1*	*131*	*0.4*	*1.1*	*0.61*	*bdl*	*6.6*	*0.05*	*48*	*0.15*	*0.02*	*0.12*	*67*	*0.12*	*0.11*
P-2	**327**	**19**	**20**	**12.1**	**88**	**62**	**2.37**	**2.6**	**11.7**	**598**	**2.0**	**1.6**	**0.09**	**0.13**	**14.2**	**0.14**	**228**	**2.48**	**0.12**	**0.30**	**25**	**1.43**	**0.88**
	49	*4*	*4*	*5.5*	*77*	*28*	*0.81*	*0.9*	*1.2*	*100*	*0.6*	*1.6*	*0.10*	*0.15*	*9.6*	*0.06*	*165*	*1.20*	*0.04*	*0.50*	*28*	*0.42*	*0.31*
P-3	**208**	**13**	**39**	**13.8**	**20**	**22**	**2.27**	**1.6**	**15.6**	**449**	**1.2**	**1.6**	**bdl**	**bdl**	**5.9**	**0.14**	**121**	**1.31**	**0.08**	**0.27**	**9**	**1.08**	**0.52**
	27	*7*	*42*	*5.7*	*41*	*9*	*0.56*	*0.7*	*1.4*	*45*	*0.3*	*0.8*	*bdl*	*bdl*	*5.8*	*0.04*	*34*	*0.71*	*0.02*	*0.19*	*23*	*0.29*	*0.06*
P-4	**468**	**39**	**106**	**273**	**3987**	**740**	**8.12**	**22.1**	**11.3**	**481**	**3.3**	**5.6**	**0.57**	**0.11**	**27.9**	**0.29**	**281**	**3.07**	**0.18**	**0.35**	**227**	**2.46**	**1.07**
	84	*11*	*51*	*234*	*1665*	*434*	*1.70*	*11.4*	*3.5*	*131*	*0.7*	*2.7*	*0.29*	*0.13*	*30.2*	*0.12*	*70*	*1.30*	*0.04*	*0.34*	*169*	*0.80*	*0.23*

Table 7.3. The Rare Earth Elements for the four plant ash groups. Concentrations in ppm. Eu = Eu anomaly, calculated as described in Chapter 5. La/Yb is the ratio of LREE to HREE. Total REE = sum of the REE elements.

Group		Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu	La/Yb	Total REE
P-1	**M**	**7.7**	**7.4**	**13.5**	**1.7**	**7.0**	**1.4**	**0.4**	**1.2**	**0.2**	**1.1**	**0.2**	**0.6**	**0.1**	**0.6**	**0.1**	**0.28**	**12.7**	**43.4**
	S.D	*1.1*	*0.7*	*1.6*	*0.2*	*0.7*	*0.2*	*0.0*	*0.2*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.02*	*1.0*	*4.6*
P-2	**M**	**5.1**	**6.7**	**12.8**	**1.4**	**5.3**	**1.0**	**0.2**	**0.7**	**0.1**	**0.8**	**0.2**	**0.4**	**0.1**	**0.5**	**0.1**	**0.19**	**14.8**	**35.3**
	S.D	*0.5*	*1.3*	*2.4*	*0.3*	*1.1*	*0.2*	*0.1*	*0.2*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.06*	*3.2*	*5.5*
P-3	**M**	**3.7**	**4.1**	**8.0**	**0.9**	**3.4**	**0.7**	**0.1**	**0.5**	**0.1**	**0.6**	**0.1**	**0.3**	**0.0**	**0.4**	**0.1**	**0.19**	**11.4**	**22.9**
	S.D	*0.8*	*1.4*	*2.6*	*0.3*	*1.1*	*0.2*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.04*	*1.6*	*6.7*
P-4	**M**	**7.5**	**9.9**	**19.5**	**2.2**	**8.2**	**1.6**	**0.3**	**1.3**	**0.2**	**1.2**	**0.2**	**0.7**	**0.1**	**0.7**	**0.1**	**0.23**	**13.9**	**53.7**
	S.D	*1.1*	*2.0*	*4.9*	*0.4*	*1.5*	*0.3*	*0.0*	*0.2*	*0.0*	*0.2*	*0.0*	*0.1*	*0.0*	*0.1*	*0.0*	*0.02*	*1.8*	*10.6*

7.1.2 Comparisons to Known Groups

In Chapter 4 three broad compositional types of plant ash glass were defined using their flux elements. This was accomplished by the critical evaluation of literature glass data taken from three regions: Syro-Palestine, Egypt and Mesopotamia. The investigation found that the flux elements from selected vessels of these regions divided into three principal plant ash types, these were termed Eastern Mediterranean, Mesopotamian Type 1 and Mesopotamian Type 2. These broad groups were based on the plant ash and each contains more than one production group as defined by their sand source.

The three flux groups and their associated production groups are:

Eastern Mediterranean which incorporates glass from Tyre (Freestone 2002), Banias (Freestone et al 2000) and Raqqa (Raqqa Type 1; Henderson et al 2004) but also glass weight standards from Fustat (Group 3A; Gratuze and Barrandon 1990).

Mesopotamian Type 1 contains the groups Nishapur Coloured (Brill 1995), Samarra Type B (Wypyski 2015) and the Sasanian 1a and b (Mirti et al 2008; 2009).

Mesopotamian Type 2 encompasses the groups Nishapur Colourless (Brill 1995), Samarra Type A (Wypyski 2015), Henderson's Samarra data (Henderson et al 2016) and the Sasanian 2 (Mirti et al 2008; 2009).

The Raqqa Type 4 glass (Henderson et al 2004) covers both Mesopotamian flux groups. Full explanation of these groups can be found in Chapter 4, along with reference data averages in Table 4.1. The identified groups from this study will be compared against, firstly, these flux groups, and secondly, the regional production groups as principally defined by their silica source. A summary of the data sources for all the comparative data used in this section is presented in Table 7.4.

Figure 7.3 presents the results of PCA conducted on the identified groups (P-1, P-2, P-3, P-4) alongside a range of literature compositional data. The chosen comparative data represent the main regional compositional groups mentioned above. Comparisons were also made to Egypt Group 3 (A) (Gratuze and Barrandon 1990) and samples from Banias (Phelps and Freestone, Appendix B) but matches were not identified and these data were removed from the image for clarity.

P-1 and P-2 (a & b) fall into the Eastern Mediterranean area of Figure 7.3, with P-1 closely matching production from Tyre. The P-2a and b groups fall to the upper and right edges of the P-1 cluster showing similarities to Tyre but without an exact match. The P-3 samples fall into the Mesopotamian Type 2 region, with the majority of the samples being closely associated with the Nishapur Colourless group, although 3 samples stray into the region occupied by Mirti et al's Sasanian 2. The P-4 group inhabits the region of Mesopotamian Type 1, and is found in close association with the Nishapur Coloured group. An overview of the results of this comparison is presented in Table 7.5.

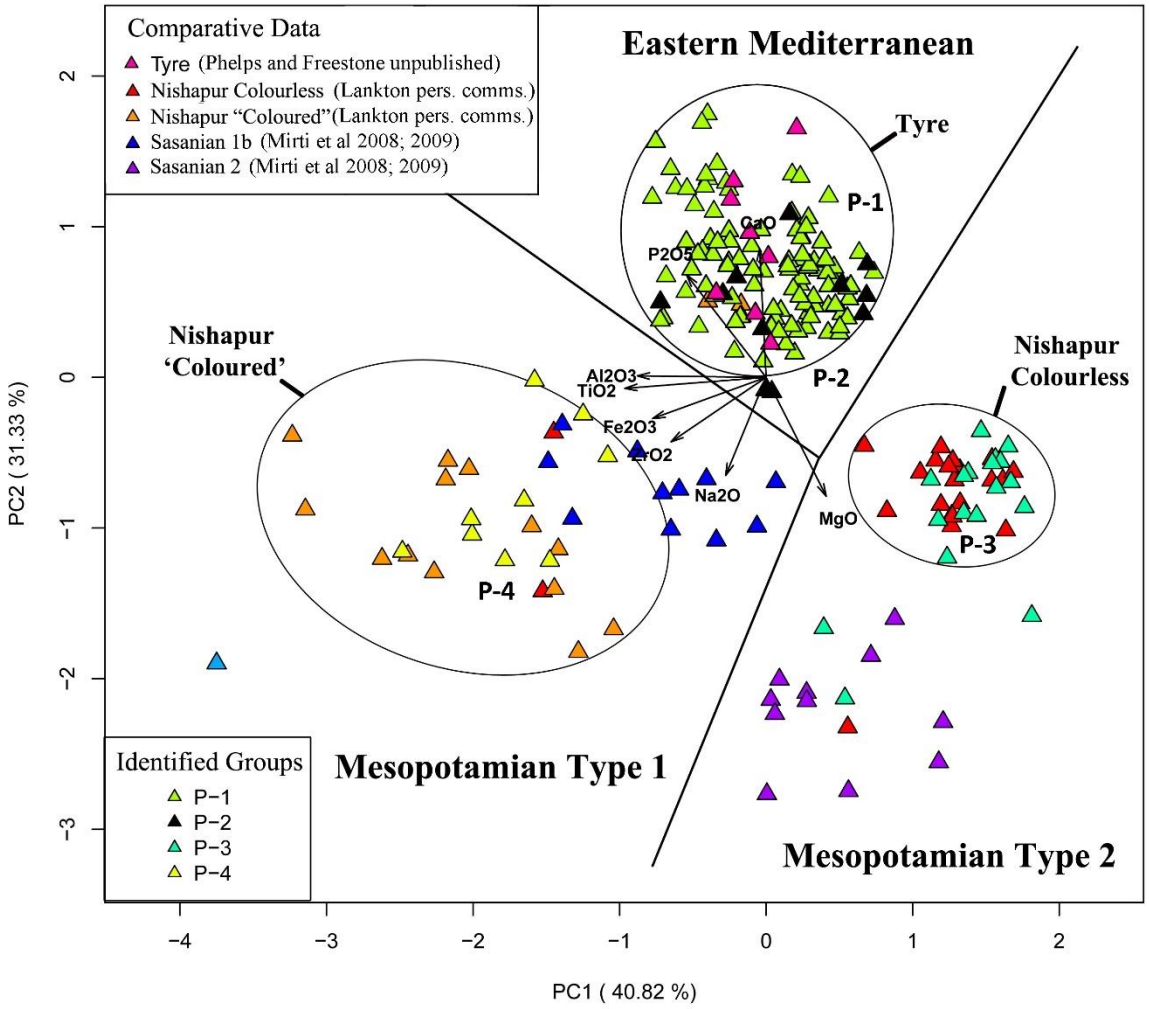


Figure 7.3 PCA bi-plot of the identified groups compared with compariative data. The Eastern Mediterranean, Mesopotamian Type 1 and Mesopotamian Type 2 flux types are labelled. Circles added manually and identify production types. The oxides used are as Figure 7.1 but with the addition of Na_2O and TiO_2. The four identified plant ash groups can be characterised into Eastern Mediterreanean (P-1 and P-2), Mesopotamian Type 1 (P-4) and Mespotamian Type 2 (P-4).

Table 7.4 Summary of comparative data sources used in this chapter, showing original sample publication and reanalysis information.

Site	Group Name	Original Publication	Method	Number	Trace Elemental Re-analysis	Method	Number
Plant Ash Glass							
Tyre	Tyre Tyre Co-blue	Freestone 2004	SEM-EDX	12	Phelps and Freestone (Appendix B)	LA-ICP-MS	7 1
Banias	Banias	Freestone 2000	SEM-EDX	18	Phelps and Freestone (Appendix B)	LA-ICP-MS	12
Raqqa	Raqqa Type 1 Raqqa Type 4	Henderson 1999/ Henderson et al 2004	WDS	90 73	Henderson et al 2016	LA-ICP-MS	7*
Egypt	Group 3A†	Gratuze and Barrandon 1990	NAA	7	N/A		
Nishapur	Nishapur Colourless Nishapur Coloured Nishapur Cobalt‡	Brill 1995	AAS	18 23	Lankton unpublished	LA-ICP-MS	23 15 8
Sasanian	Sasanian 1b Sasanian 2	Mirti et al 2008; 2009	sol ICP-MS	11 13	N/A		
Samarra	Samarra Type A Samarra Type B	Wypyski 2015 (data pers. comms)	WDS	44 12	N/A		
Samarra	(Samarra Type A/ Nishapur Coloured?)	Henderson et al 2016	LA-ICP-MS	21	N/A		
Natron Glass							
El Ashmunein	Egypt II	Bimson and Freestone 1985	SEM-EDX	4	Phelps and Freestone (Appendix A)	LA-ICP-MS	4
Apollonia	Apollonia Type/Levantine I	Freestone et al 2000	SEM-EDX	9	Lankton and Freestone (Appendix A)	LA-ICP-MS	5
Bet Eli'ezer	Bet Eli'ezer/Levantine II	Freestone et al 2000	SEM-EDX	27	Lankton and Freestone (Appendix A)	LA-ICP-MS	5
Scratch Decorated Samples[1]	Egypt II Cobalt	Brill 1999B	AAS	8			

* Separation of this group performed by author using compositions defined in Henderson et al 2004; † Group 3A defined by author as a sub-set of Gratuze and Barrandon's Group 3; ‡ Authors designation, a sub-set of the cobalt blue samples from the Nishapur Coloured group; [1] Samples chosen which fit an 'Egypt II' composition

Table 7.5. An overview of the four groups identified in Figure 7.2 with their flux type, production type and matching comparative glass. For the flux type definitions seen Chapter 4.

Identified Group	Flux Group	Production Type	Comparative Groups
P-1	Eastern Mediterranean	Tyre Type	**Tyre** (Phelps and Freestone, Appendix B)
P-2 (a and b)	Eastern Mediterranean	Unknown Syro-Palestine Type	**Raqqa Type 1** (Henderson et al 2004) **Banias?** (Phelps and Freestone, Appendix B)
P-3	Mesopotamian Type 2	Nishapur Colourless/Samarra Type A	**Nishapur Colourless** (Lankton pers. comms.) **Samarra Type A** (Wypyski 2015) **Samarra** (Henderson et al 2016) **Sasanian 2** (Mirti et al 2008; 2009)
P-4	Mesopotamian Type 1	Nishapur Coloured/Samarra Type B	**Nishapur Coloured** (Lankton pers. comms.) **Samarra Type B** (Wypyski 2015) **Sasanian 1b** (Mirti et al 2008; 2009)

7.2 Group Characterisation

7.2.1 Introduction

Plant ash glass is compositionally more complex than natron glass. The plant ash, as discussed in Chapter 5, imparts a number of flux elements (e.g. Na, Mg, K, Ca, P) as well as some minor and trace elements (e.g. Sr, Rb, Al and Fe). The silica source contains a number of elements representing the components of accessory minerals (e.g. Fe, Al, Ti, Zr) along with certain associated trace elements (e.g. Cr, Mo, Hf, Ba). Furthermore, some trace elements, including the REE, are inputted not only by the minerals associated with the silica source but also the clay fraction of the sand, and therefore reflects the geological history of the sand. These elements might also be affected by the soil incorporated in the plant ash. Such differing inputs allow the chemical separation of glass at various levels; by their plant ash, sand mineralogy or by regional geology. Therefore, the identified groups will be defined, firstly, by their flux content and secondly, by their mineralogical and geochemical content. This recognises that the glasses may be similar at one level but different at another. For example, that two glass groups can share the same plant ash type but differ in their sand and geochemistry, or that two glass groups share a regional geochemistry but differ in their plant ash and accessory minerals of their sand.

This section will further characterise the composition of the identified groups and confirm their associations to known types.

7.2.2 The Syro-Palestine Glass

The Eastern Mediterranean flux group is characterised by elevated CaO, low MgO, and a low P_2O_5/K_2O ratio. Groups P-1 and P-2 fall into this category.

7.2.2.1 P-1: The Tyre Glass

P-1 is the largest group, containing 102 vessels. In flux oxides the group is characterised by relatively low magnesia (av. 3.0%, range 2-4%) and high lime (av.

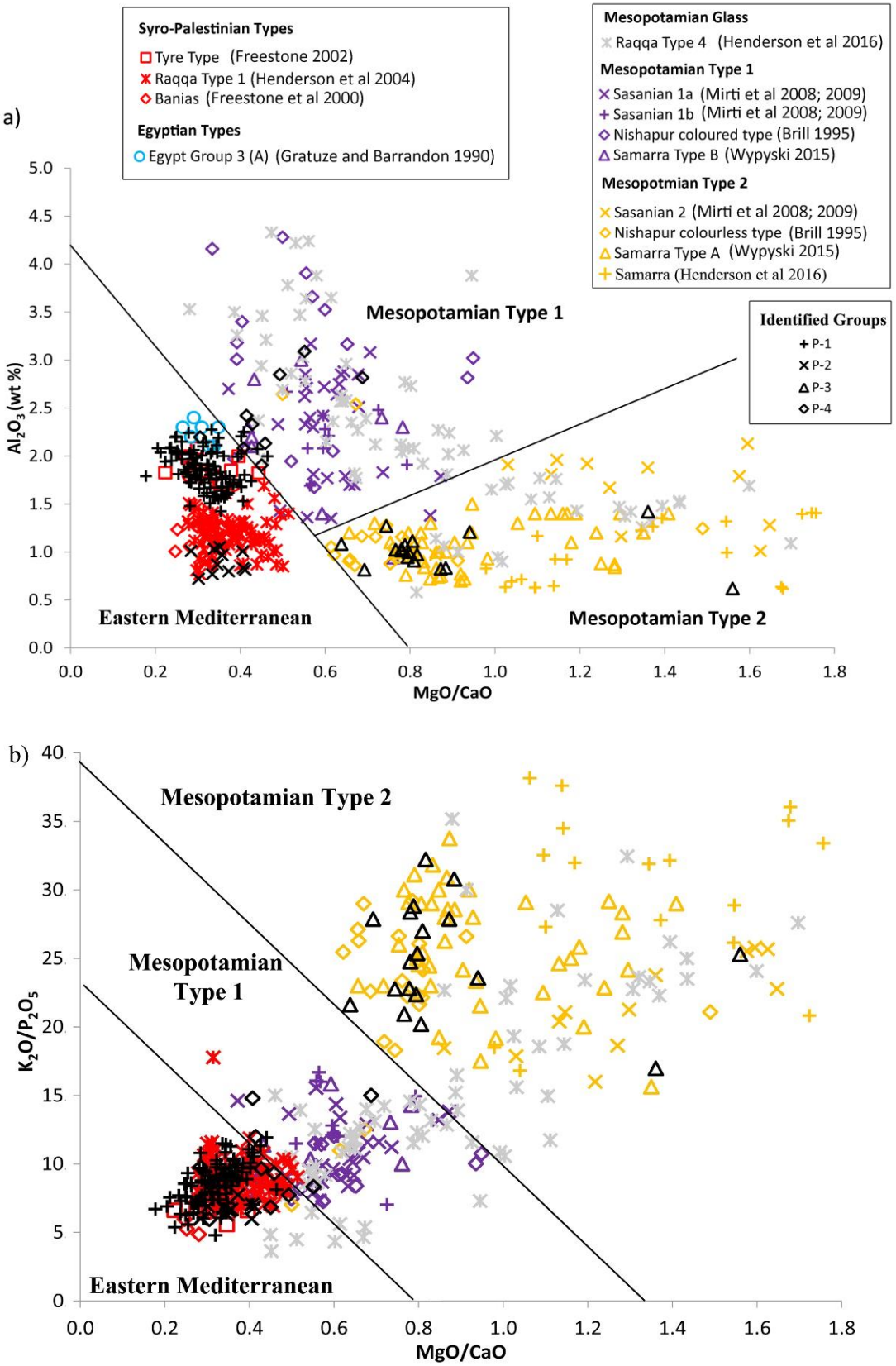


Figure 7.4 Comparison of the identified groups against a range of comparative plant ash glass data from Syro-Palestine (Tyre, Raqqa, Banias), Egypt (Group 3A) and Mesopotamia (Nishapur, Samarra and Sasanian glass from Veh Ardasir). Data sources in key. a.) Al_2O_3 against MgO/CaO; b) K_2O/P_2O_5 against MgO/CaO. Note, no Egyptian data in this figure.

9.5%), giving mean MgO/CaO and K_2O/P_2O_5 ratios of 0.32 and 8.41 respectively (Table 7.1). These values are similar to the ratios of glass from Tyre (av. 0.23 and 6.75), as well as the other Eastern Mediterranean glass from Banias (0.28 and 6.45), Raqqa (Type 1: 0.37 and 8.84) and Egyptian Group 3A as reported in Table 4.2. These similarities are demonstrated in Figure 7.4 (a & b), and suggest a commonality in flux usage within the Eastern Mediterranean region. This could be due to the use of similar recipes and technology, e.g. the same plant species and ashing techniques, and/or due to a shared regional geology and environment which might favour certain plant species with certain plant chemistries.

Lime is a distinguishing feature of P-1. It is high and has the largest standard deviation of the flux oxides (S.D. 1.03%). CaO seems to have been close to excess in these glasses as evidenced archaeologically by the finding of large quantities of lime-rich glass waste at the Tyre production site (Freestone 2002). In comparison, the glass from Nishapur (Chapter 4, Table 4.1) has magnesia as the largest flux contribution after soda and has the largest variance (S.D. 1.22%, Nishapur Coloured). Neither of these oxides are volatile and so are not affected by ashing, therefore differences are probably geological with Syro-Palestine and Egyptian glasses dominated by lime and Mesopotamian glass by magnesia. Freestone (2006, 205) suggests magnesia-rich alluvium from the Tigris and Euphrates may have played a factor in this, while the geology of the Levant was dominated by limestone (Neev and Ben-Avraham 1977; Beydoun 1977).

In the sand-related elements alumina is high (av. 1.9%) and heavy mineral oxides are low (0.08% TiO_2; 0.5% Fe_2O_3; 48ppm ZrO_2) demonstrating close affinity to Tyre production as demonstrated in Figures 7.5 (a & b). As well as being distinct from Syrian and Egyptian glass, the P-1 group also separates from the Levantine Natron glass (groups N-1 and N-2 representing Apollonia and Bet Eli'ezer Types respectively) with around 1.5-2% less Al_2O_3 but the same ZrO_2 and TiO_2 content. This demonstrates that the mineral mixture of the sands differ in terms of feldspar between Tyre and Palestine but the heavier mineral (titania and zirconia) content remains similar.

The TiO_2 content of P-1 varies quite considerably (range 0.05-0.13%). TiO_2 correlates with Al_2O_3 (r^2=0.68) and ZrO_2 (r^2= 0.91), and thus seems to be attributed to natural

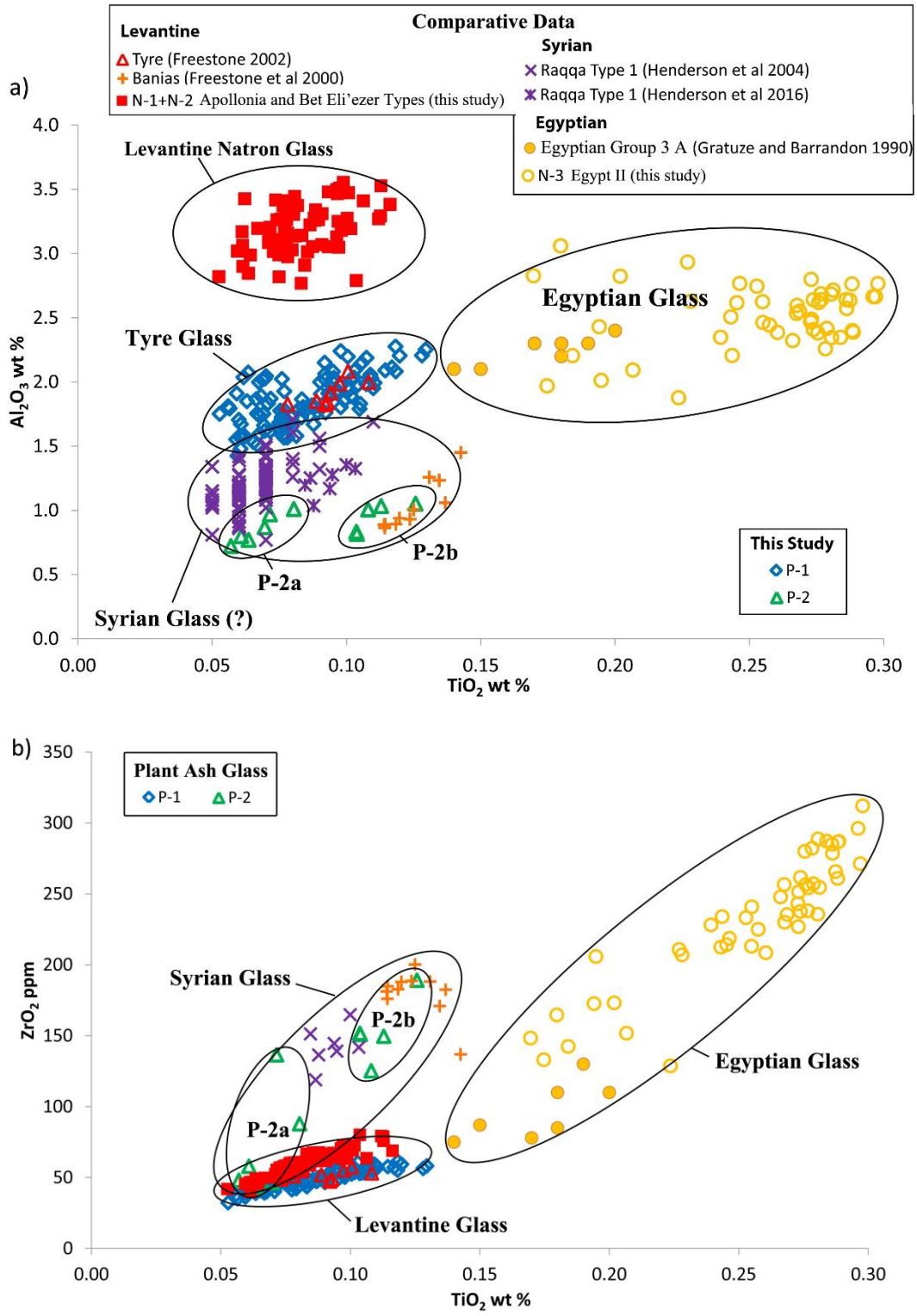


Figure 7.5. Comparison of groups P-1 and P-2 against a range of comparative glass (plant ash and natron) centred around the Levant (Tyre and Levantine natron glasses), Egypt (Group 3A and Egypt II) and Syria (Raqqa Type 1 and Banias). P-2a and 2b groups are circled. a) Al_2O_3 versus TiO_2 and b) ZrO_2 versus TiO_2. The images demonstrate the similarity of P-1 to Tyre glass types and the minerological similarity between Tyre and other Levantine glasses in titania and zirconia. The split within P-2 is shown, although overall the groups tend to be similar to Syrian glass types.

variations in the sand. To investigate whether this variation has any archaeologically meaningful pattern, the vessels of P-1 are grouped by location (Figure 7.6a) and time period (Figure 7.6b), however no correspondence between composition and location or chronology was identifiable with the exception of samples from CEA 6194 which appear to form a reasonably tight compositional group. This grouping may well represent a batch, rather than a distinct production type. It suggests that variation within the titania and zirconia is naturally occurring within the sand, and not based on contextual differences.

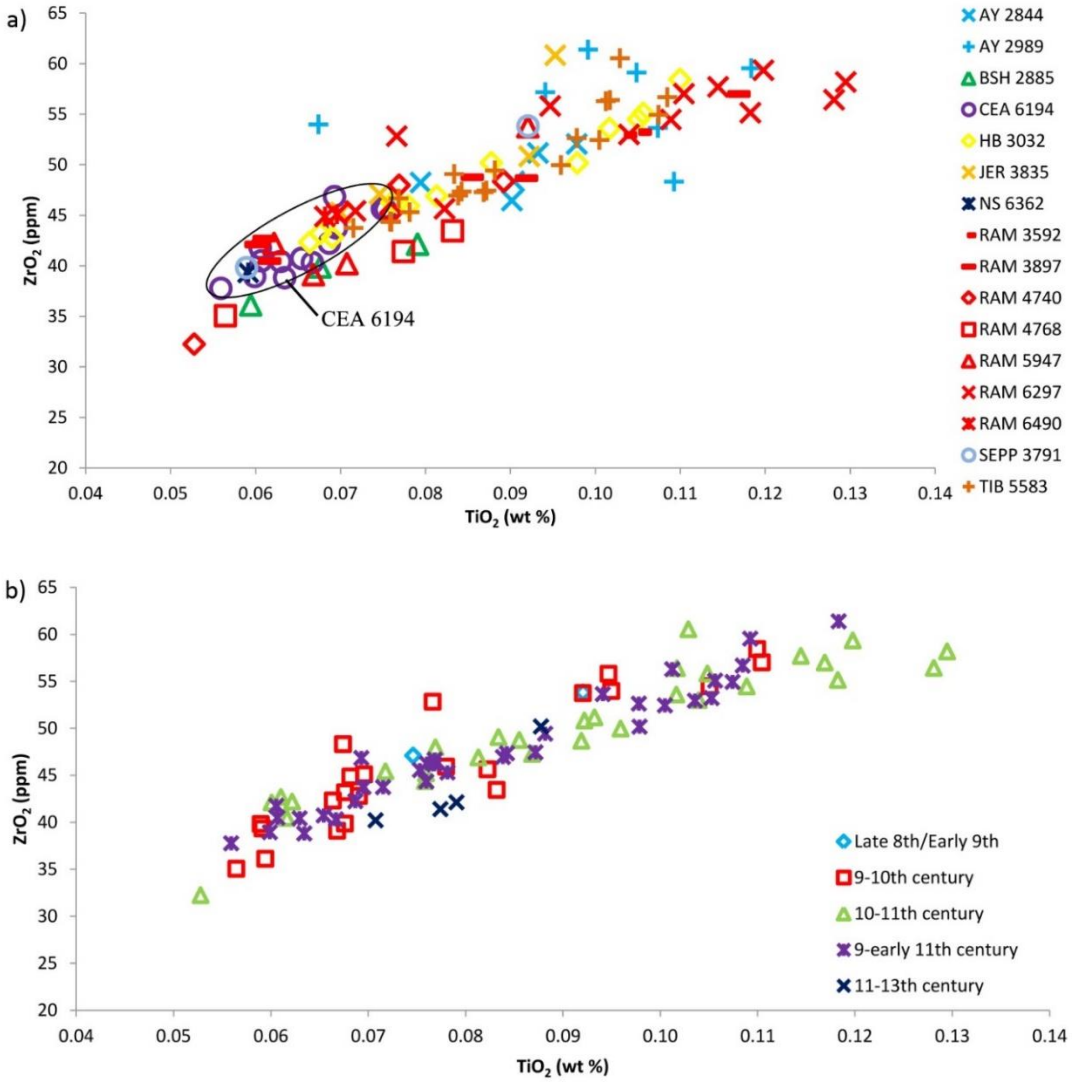


Figure 7.6. ZrO_2 versus TiO_2 for P-1 grouped by site in (a) with locations colour coded, and P-1 grouped by date in (b). There is no clear link between location or time period with composition, although samples from CEA 6194 have clustered on one region (marked).

The trace elements content of P-1 is generally low (Figure 7.7a), similar in many respects to the P-2 and P-3, although differences in Cr, Zr and Ba highlight the distinctiveness of P-1 compared to these groups. In the REE (Figure 7.7b) the individuality of P-1 is more clearly seen with a pronounced negative Ce anomaly and positive Eu anomaly relative to MUQ which is unique among the identified groups. Total REE is also generally high (Table 7.3).

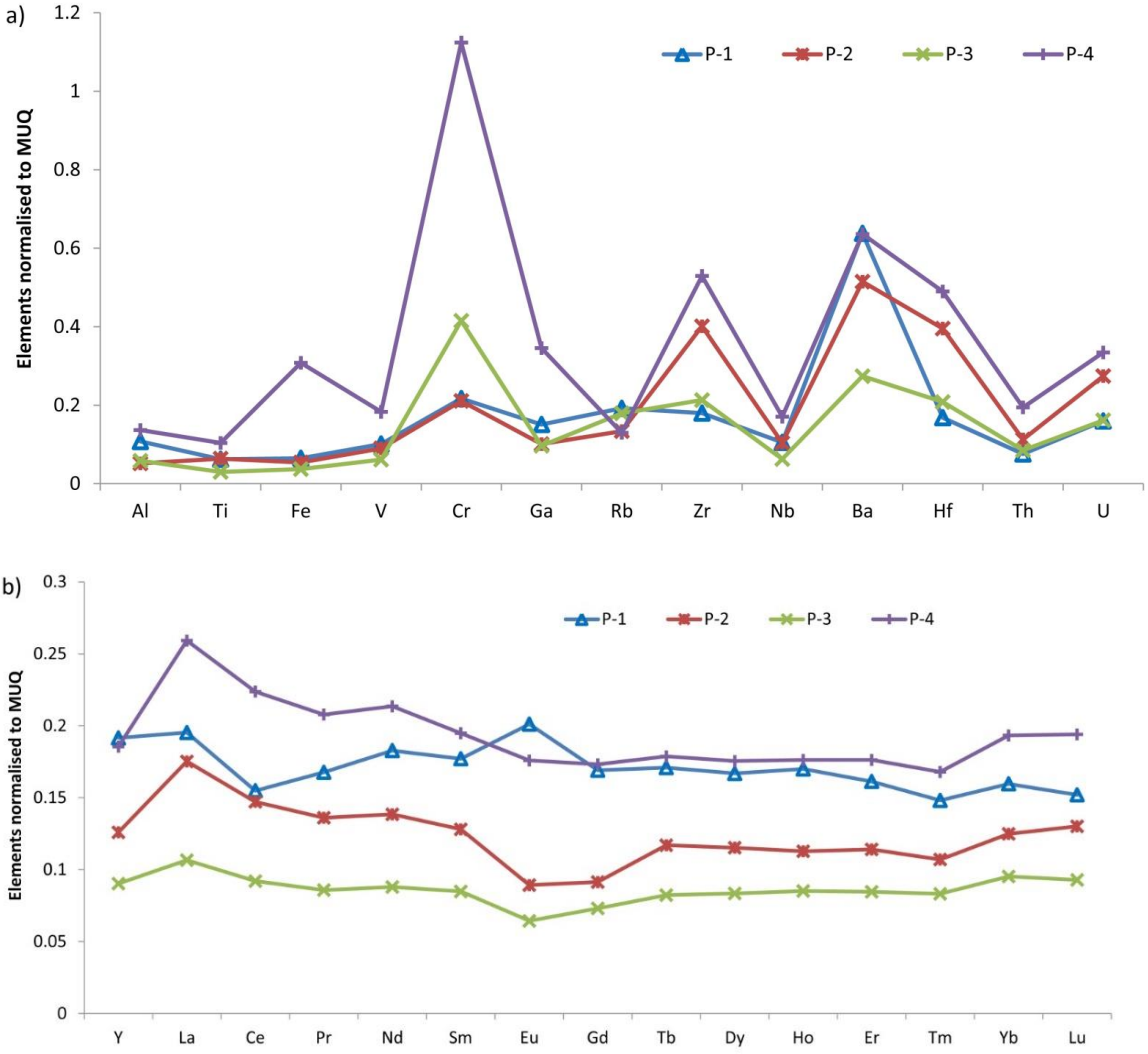


Figure 7.7. A comparison of selected major, minor and trace elements in (a) and REE in (b). All values normalised to weathered continental crust (MUQ; Kamber et al 2005). The elements used here give an indication of the minerology and geochemistry of the silica sources in the glass. Note, the positive Eu anomaly of P-1 not seen in the other groups.

In comparison to literature groups of Levantine glass from Tyre and natron glass from Apollonia and Bet Eli'ezer in Figure 7.8 (a & b), P-1 and Tyre demonstrate an exact

match in the minor and trace elements, except for a slight reduction in Ga in P-1. Both plant ash glass groups also show an extremely close match with the natron glass, with only a few differences. These includes a difference in Al already mentioned above. U is higher in the natron glass, probably due to its contribution in the natron (Degryse and Shortland 2009). Similarly, Rb is raised in the plant ash glass due to its association with potassium contained within plant ash. Ba is also raised in the plant ash glass, probably elevated through the contribution of manganese oxide as a decolourant, Ba is a known

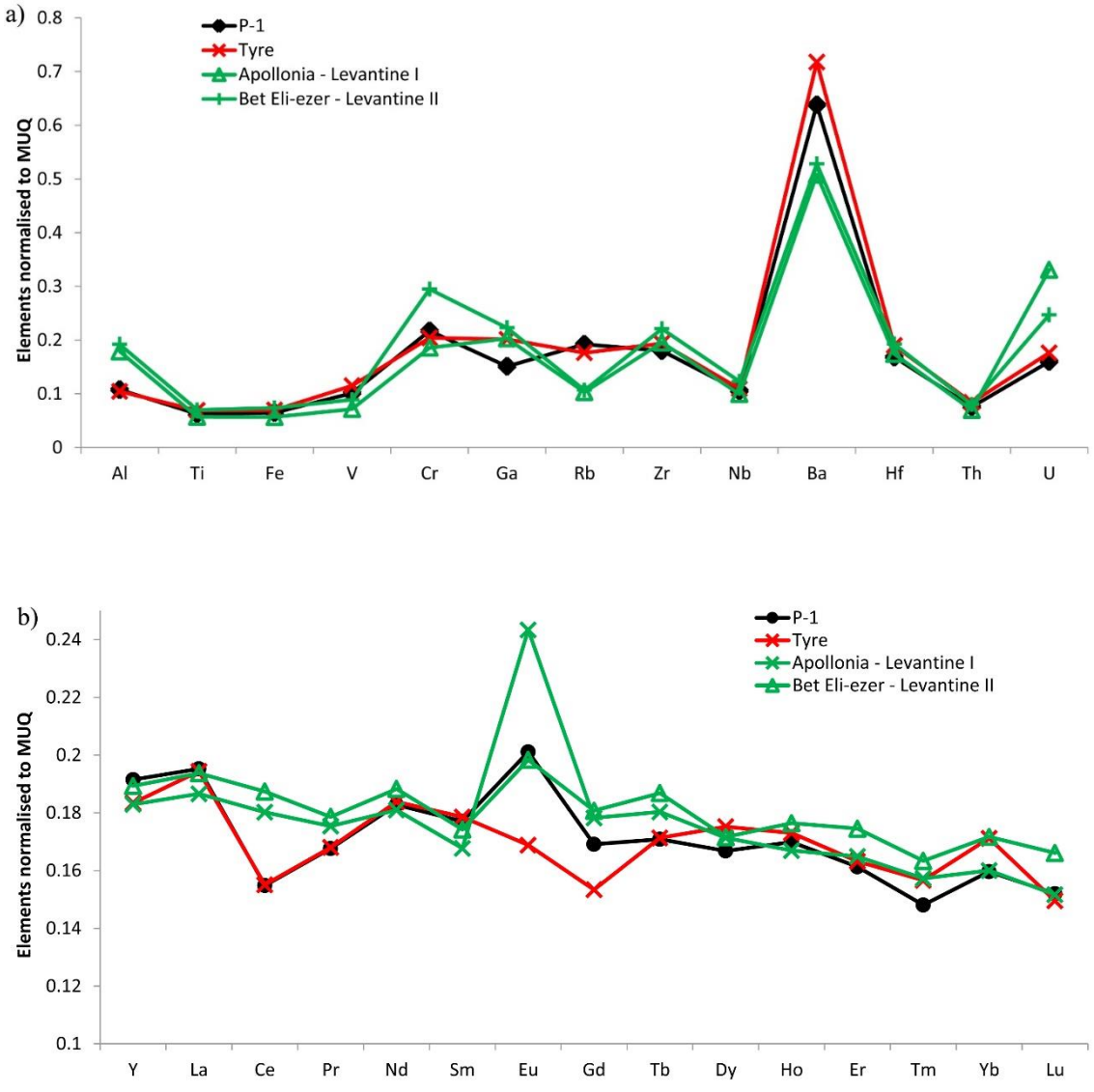


Figure 7.8. Comparison of selected major, minor and trace elements in (a) and REE in (b) of the Levantine glasses: P-1, Tyre (Phelps and Freestone unpublished) and Levantine Natron glass (Apollonia and Bet Eli'ezer; Lankton and Freestone unpublished, see Appendix A). Groups demonstrate very similar profiles in both images indicating the sands came from similar geologies. The data is normalised to MUQ.

impurity of manganese oxide, see Section 7.6.2. For the REE (Figure 7.8b) a similar picture of close correspondence is observed. P-1 matches the Tyre reference data in almost all elements, with only some divergences in Eu and Gd, of which the Tyre glass has less of both, and also a lack of positive Eu anomaly seen in P-1 and the natron glass. Very close agreement is seen to the natron groups, with only the negative Ce anomaly of the plant ash glasses demonstrating difference. The reasons for this is not known.

The key finding of this comparison is that despite differences in the sand mineralogy, which makes plant ash and natron groups clearly distinguishable, their trace and REE indicate a very close affinity and confirm the shared geochemical setting. Comparisons of P-1 to Egypt II, Banias and Raqqa Type 1 groups were also made but not shown, in this comparison clear divergences between the groups were seen in the trace elements.

In summary, compositional comparisons have shown P-1 to have a composition similar to that identified from the primary production site of Tyre, but also with close geochemical similarities to the natron glasses made along the Levantine coast. The sands used for production at Tyre were most likely locally sourced. This is attested by William of Tyre, who, writing before 1185, reports that glassmaking sand was collected *"on the same plain"* as Tyre (Carboni et al 2003, 146). The city of Tyre is situated in a coastal location within the Nile littoral cell. It therefore receives Nilotic sediments being swept anti-clockwise around the Eastern Mediterranean by long-shore drift. The contribution of Nile sediment to Tyre glass is demonstrated in the high εNd (-5 to -3) of the glass, which is a characteristic of Nile material (Freestone et al 2009B). Therefore, the sand used at Tyre is geochemically similar to that from Israel, however, the mineralogy of the sands are very different. The sand used in glass production at Apollonia and Bet Eli'ezer were lime and alumina rich, while the sand used at Tyre had approximately half the alumina content and were low in lime (Freestone 2002), with the lime being provided by the plant ash. The sand at Tyre may be different in relation to those sands in Palestine due to the effects of the depositional environment, this appears to have had a large effect on the feldspar content but much less so on the

heavy minerals, although Tyre and P1 have on average slightly lower Zr content than the Levantine natron glass.

Geological surveys along the coast of Tyre have found the sand to be almost entirely calcareous, mainly created from the erosion of calcium carbonate-rich coastal ridges called *'hajor ramli'* (Nir 1996; Beydoun 1976). A quartz-rich sand is found 7km to the north of Tyre, at the mouth of the River Litani which carries an outflow of eroded Lower Cretaceous sandstone (Nir 1996, 241), however even these sands are recorded as having 18-35% $CaCO_3$ (ibid). It appears that the sands used for glass production at Tyre seem to be especially low in lime compared to the general trend of sands of the region. This may suggest that they were chosen specifically from rarer deposits, possibly from a more inland location, although still containing a contribution of Nile sediments.

The P-1 group had added manganese oxide throughout ranging from 0.05% to 2% (av. 1%).

7.2.2.2 P-2: Unknown Syro-Palestine Glass

P-2 is a small group of 11 vessels which share the low MgO/CaO and K_2O/P_2O_5 ratios (0.35 and 6.8; Table 7.1) common to the Eastern Mediterranean flux type (Figure 7.4 a & b). In sand-related elements the group is categorised by very low Al_2O_3 (av. 0.9%), low TiO_2 (av. 0.09%) and Fe_2O_3 (av. 0.42%), although ZrO_2 is relatively high (108ppm; Figure 7.5a & b). This group also has some of the lowest levels of total REE (35ppm). It equates to a high silica sand with few accessory minerals, especially feldspar, although with a zircon component higher than that of glass from Tyre. However, as mentioned previously, Figure 7.1 suggested the splitting of P-2 into two groups of 5 (P-2a) and 6 (P-2b) samples. Labelled circles within Figures 7.5a & b highlight these two sub-groups. The differentiation of P-2a from P-2b is mainly by Al_2O_3/TiO_2 and Al_2O_3/ZrO_2 ratios, with P-2a higher in both. (Note that group population has been slightly modified from that presented in Figure 7.1 by reallocating RAM 4740-05 to P-2a based on these ratios). Mean values for each group are shown in Table 7.6. The differing ratios suggest the use of sand deposits with differing mineral contributions. Some disparities are also

recognised in the flux with P-2a containing around 3% more soda, implying the use of a slightly different plant ash. Manganese oxide content also varies, and is found at <0.1% in P-2a (with the exception of RAM 4740-05) but deliberately added to P-2b at 0.4-1.0%. However, despite these variances, compositionally these groups are still very similar, however, this separation is confirmed by their differing contexts. The samples of P-2a come from a range of sites (see Appendix J) dating from the late 8th/early 9th - 11th century, and one sample (BSH 2885-03) dating to the 11th-13th century. P-2b, on the other hand, contains vessels from Bet Shean only, and date to the 11th-13th century. The spatial and chronological separation strongly suggest that they represent distinct productions.

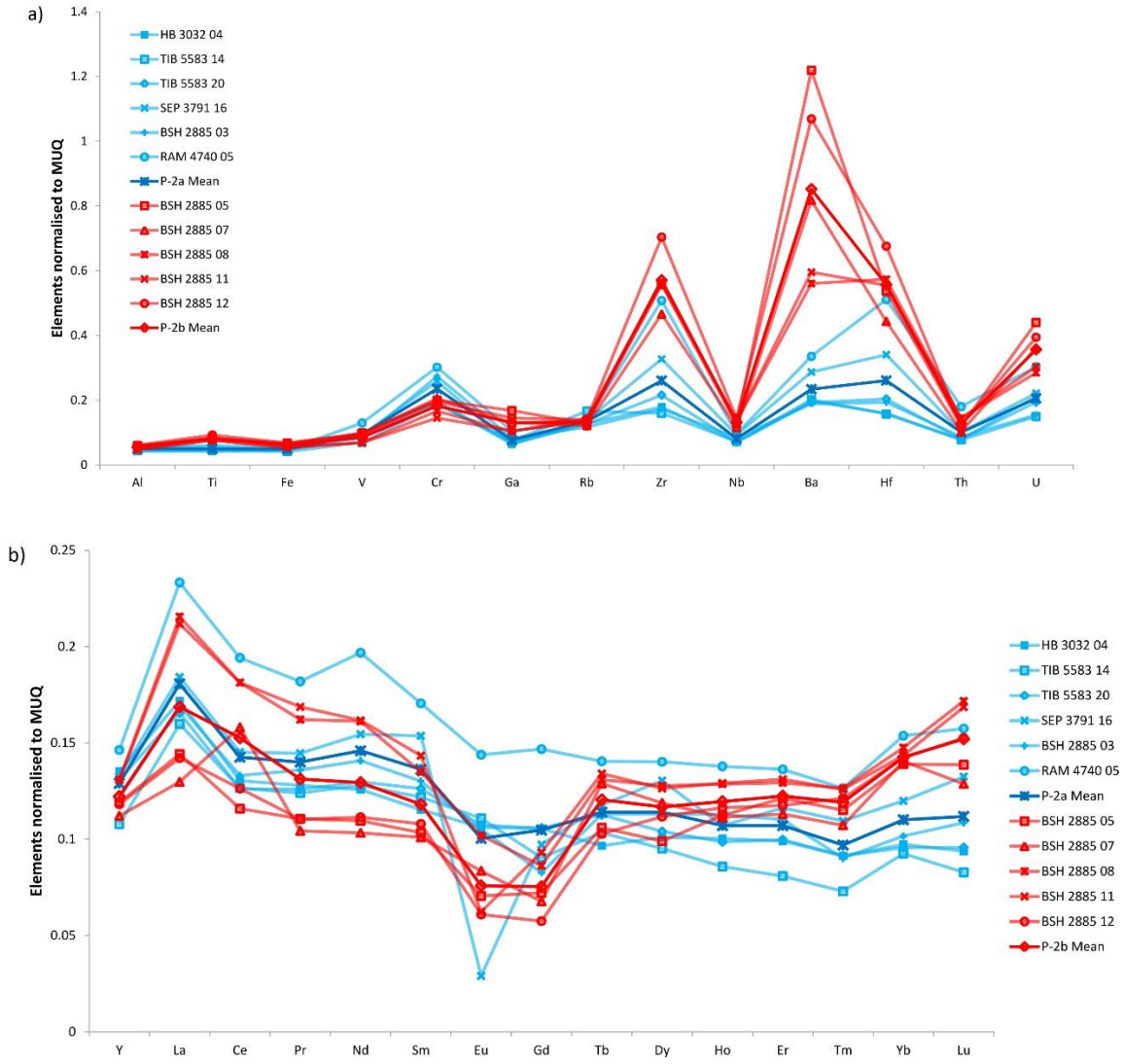


Figure 7.9. Line graph of selected major, minor and trace elements (a) and REE (b) for P-2a (blue) and P-2b (red). Means are shown as darker coloured lines. Image demonstrates systematic differences between the groups. Data normalised to MUQ.

Table 7.6. P-2 (a & b) group means and standard deviation. Wt % unless otherwise stated. Oxides removed for being bdl = Li_2O, In, Au, Bi, Pt, Se.

Major, Minor, selected trace oxides

Group	N	Colour*		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO	CoO†	SrO†	ZrO_2†	MgO/CaO	K_2O/P_2O_5
P-2a	6	Light bluish-green	**M**	**13.78**	**3.30**	**0.86**	**67.78**	**0.34**	**0.79**	**2.36**	**9.96**	**0.07**	**0.37**	**0.25**	**3**	**661**	**70**	**0.33**	**6.96**
			S.D	*1.09*	*0.33*	*0.11*	*1.30*	*0.03*	*0.11*	*0.22*	*0.86*	*0.01*	*0.04*	*0.47*	*2*	*71*	*36*	*0.38*	*7.14*
P-2b	5	Colourless	**M**	**11.07**	**3.40**	**0.95**	**71.10**	**0.32**	**0.71**	**2.12**	**8.91**	**0.11**	**0.48**	**0.65**	**17**	**523**	**153**	**0.38**	**6.59**
			S.D	*1.43*	*0.35*	*0.11*	*1.20*	*0.07*	*0.06*	*0.35*	*0.88*	*0.01*	*0.05*	*0.25*	*6*	*77*	*23*	*0.40*	*5.00*

= most frequent vessel colour, † = in ppm

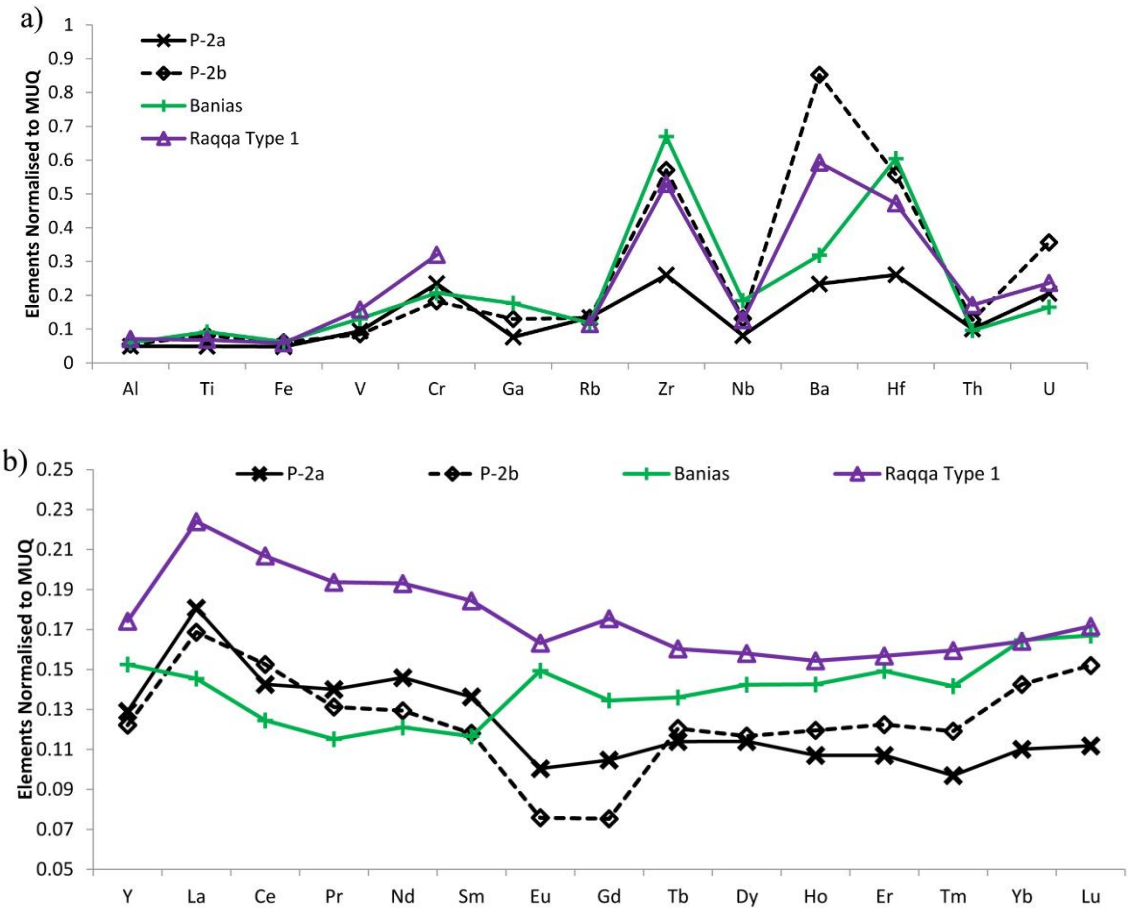
Trace oxides in ppm

Group	B_2O_3	V_2O_5	Cr_2O_3	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Nb_2O_3	MoO	Ag	Cd	SnO_2	Cs_2O	BaO	HfO_2	Ta_2O_3	WO	PbO	ThO_2	UO_2
P-2a	**347**	**20**	**22**	**16**	**30**	**48**	**1.8**	**2.5**	**11.7**	**1.6**	**1.8**	**0.11**	**bdl**	**12**	**0.7**	**0.11**	**103**	**1.6**	**0.09**	**0.3**	**30**	**1.3**	**0.7**
	59	*4*	*5*	*4*	*11*	*9*	*0.4*	*1.2*	*1.5*	*0.2*	*2.2*	*0.13*	*bdl*	*12*	*0.7*	*0.06*	*27*	*0.9*	*0.02*	*0.7*	*37*	*0.5*	*0.2*
P-2b	**303**	**18**	**17**	**7**	**157**	**79**	**3.1**	**2.8**	**11.6**	**2.5**	**1.1**	**0.06**	**0.2**	**17**	**0.9**	**0.18**	**377**	**3.5**	**0.15**	**0.2**	**18**	**1.6**	**1.1**
	21	*3*	*2*	*2*	*59*	*34*	*0.6*	*0.6*	*0.8*	*0.2*	*0.2*	*0.02*	*0.2*	*5*	*0.3*	*0.03*	*128*	*0.5*	*0.02*	*0.2*	*10*	*0.2*	*0.2*

REE Oxides in ppm

Group	Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu	La/Yb	Total REE
P-2a	**5.22**	**6.89**	**12.45**	**1.45**	**5.60**	**1.09**	**0.18**	**0.77**	**0.13**	**0.77**	**0.15**	**0.41**	**0.06**	**0.41**	**0.06**	**0.20**	**17.08**	**35.64**
	0.53	*1.03*	*2.29*	*0.23*	*1.04*	*0.17*	*0.07*	*0.16*	*0.02*	*0.12*	*0.02*	*0.07*	*0.01*	*0.09*	*0.02*	*0.07*	*1.09*	*5.60*
P-2b	**4.94**	**6.43**	**13.32**	**1.36**	**4.97**	**0.94**	**0.14**	**0.55**	**0.14**	**0.79**	**0.17**	**0.47**	**0.07**	**0.53**	**0.08**	**0.19**	**12.15**	**34.91**
	0.34	*1.58*	*2.66*	*0.33*	*1.13*	*0.16*	*0.03*	*0.11*	*0.02*	*0.08*	*0.01*	*0.03*	*0.005*	*0.01*	*0.01*	*0.04*	*2.75*	*6.09*

Compositional differences between the sub-groups are best demonstrated using elements from the sand source (Figure 7.9a & b). The samples of P-2a contains higher amounts of Cr but lower quantities of almost every other element, most notably the heavy mineral elements: Fe, Ti, Zr, Nb, Ba and Hf. It implies that P-2a used a sand deposit depleted in heavy minerals and P-2b used a sand enriched in heavy mineral and also slightly depleted in LREE, as evident from Table 7.6.

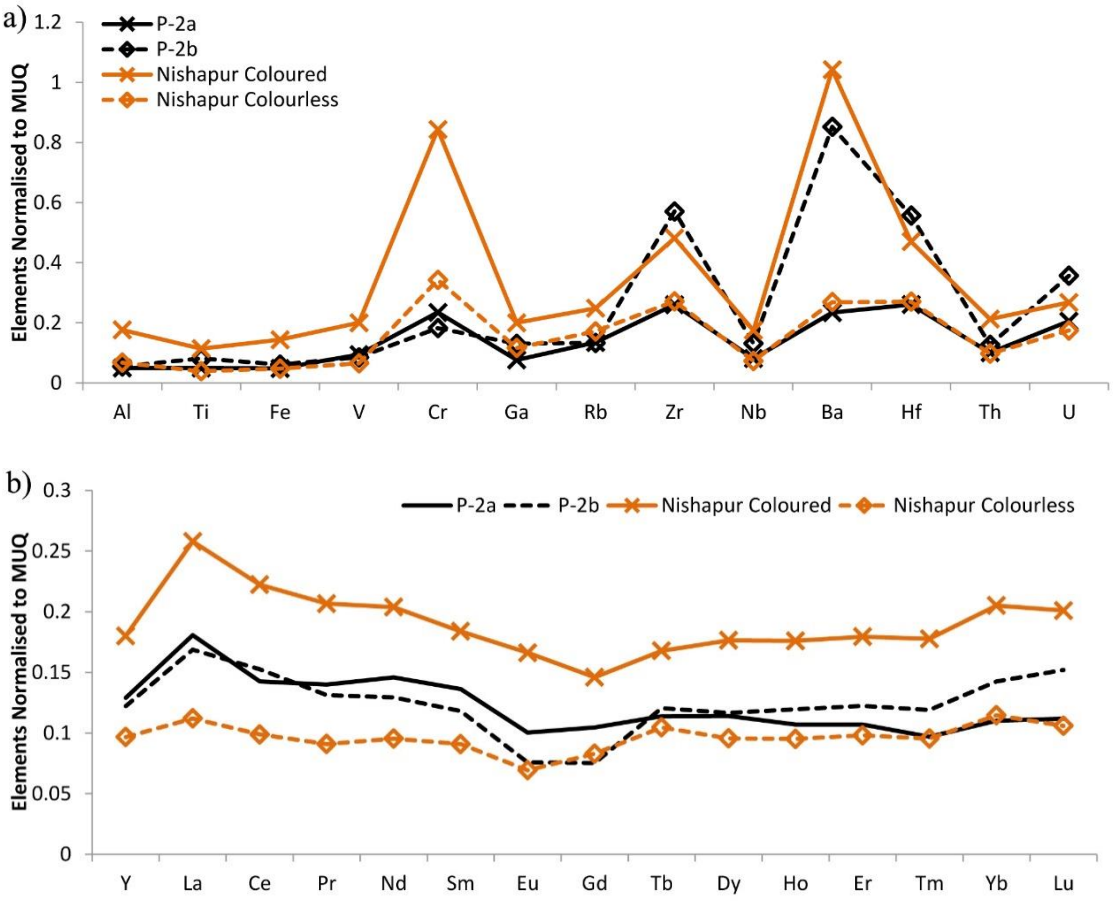


Figures 7.10. Line graphs of selected major, minor and trace elements in (a) and REE in (b) comparing P-2a and P-2b against Syro-Palestinian glass from Banias (Phelps and Freestone, Appendix B) and Raqqa Type 1 (Henderson et al 2016). The P-2 groups share a similar REE profile to Raqqa Type 1, including a negative Eu anomaly, suggesting that P-2 (a & b) are Syrian glasses. The Banias glass is different, suggesting an alternative origin.

Comparisons to other glass groups in Figure 7.5 (a & b) found that in TiO_2, Al_2O_3 and ZrO_2 P-2a showed closest similarity to Raqqa Type 1 and P-2b to samples from Banias, the latter two types also shared a 11^{th}-13^{th} century date. Further investigation was

performed using trace elements (Figure 7.10 a & b). While this confirmed some similarities between P-2b and Banias in Ga, Zr and Nb, larger differences in the strong positive Eu anomaly of the Banias glass ruled out a compositional match. P-2a and Raqqa Type 1 displayed a more successful correspondence: both have raised levels of Cr, somewhat similar Nb and Th, and negative Eu anomalies. Similar REE profiles were also noted, although elemental abundances varied. Although these matches were not exact, it can be suggested that the P-2 groups are most likely of Syrian origin, but from unidentified production locations.

A final comparison was made against Mesopotamian glass of the Nishapur Coloured and Colourless types (Figures 7.11 a & b). The aim was to investigate geochemical similarities between P-2, potentially from Syria, and Mesopotamian glass. All four



Figures 7.11. Line graphs of selected major, minor and trace elements in (a) and REE in (b) comparing P-2a and P-2b against Mesopotamian glass groups: Nishapur Coloured and Colourless. This image investigates geochemical similarities between the Syrian and Mesopotamian region. Similarities suggest that the sands of Syria and Mesopotamia share some geochemical affinity.

groups showed similarities, with negative Eu anomalies and similar REE profiles. In general, P-2b tended to match the heavy mineral element values of Nishapur Coloured and P-2a the lower quantities in Nishapur Colourless. If P-2a & b represent production in Syria, then the geochemical similarity might point to shared geological origins of the sands. It is plausible that the sands found in the floodplains near the Euphrates in Syria would share similar geologic origins to the sands found in the floodplain between the Euphrates and Tigris in Iraq as the sediments would have the same origins in the mountains of Turkey. It is reported elsewhere that the fluvial sediments of the Mesopotamian plain between the Tigris and Euphrates are very similar and well homogenised (Minc 2016, 6), potentially suggesting a regional homogeneity in the geochemistry of the sediments along the Euphrates.

To summarise, P-2a & b share a production region, but separate sites and different raw materials. They have an Eastern Mediterranean flux type and are compositionally most similar to Raqqa Type 1, although a lack of an exact match suggests an unknown production site of likely Syrian origin.

7.2.3 The Mesopotamian Glass

Mesopotamian plant ash glass has been distinguished by their higher MgO and K_2O (Freestone 2006, 204), in Chapter 4 this was expanded to include CaO and P_2O_5. The Mesopotamian glass was split into two groups based on flux content: Mesopotamian Type 1 with lower MgO/CaO and P_2O_5/K_2O ratios and Mesopotamian Type 2 with higher ratios of both; see discussion in Chapter 4. This separation is further reflected in the sand-related elements; glass of Mesopotamian Type 2 tends to utilise sand sources with fewer impurities. Twenty-eight samples were identified as Mesopotamian glass: the 18 samples of P-3 used Mesopotamian Type 2 and 10 samples of P-4 were of Mesopotamian Type 1. Table 7.5 presents a summary of which compositional group is associated to which flux type.

7.2.3.1 P-3: Nishapur Colourless/Samarra Type A

The 18 vessels of P-3 are a collection of primarily clear colourless glass with a high percentage of wheel cut examples implying that these formed a higher status glass type. The group is relatively well constrained compositionally with some of the lowest quantities of elemental impurities of any groups. Only two samples do not have colourless fabrics, CEA 6194 10 and JER 5124 31, being blue and yellowish-green respectively. In flux oxides P-3 is characterised by high magnesia (av. 5.1%), low CaO (av. 6.1%) and very low P_2O_5 (av. 0.1%). The ratios of 0.84 MgO/CaO and 24.7 K_2O/P_2O_5 equate to that of other Mesopotamian Type 2 glass, which exhibit mean ratios of between 0.8-1.3 MgO/CaO and 18.8-22.2 K_2O/P_2O_5 (not including the Samarra data from Henderson et al 2016; see Chapter 4, Table 4.2).

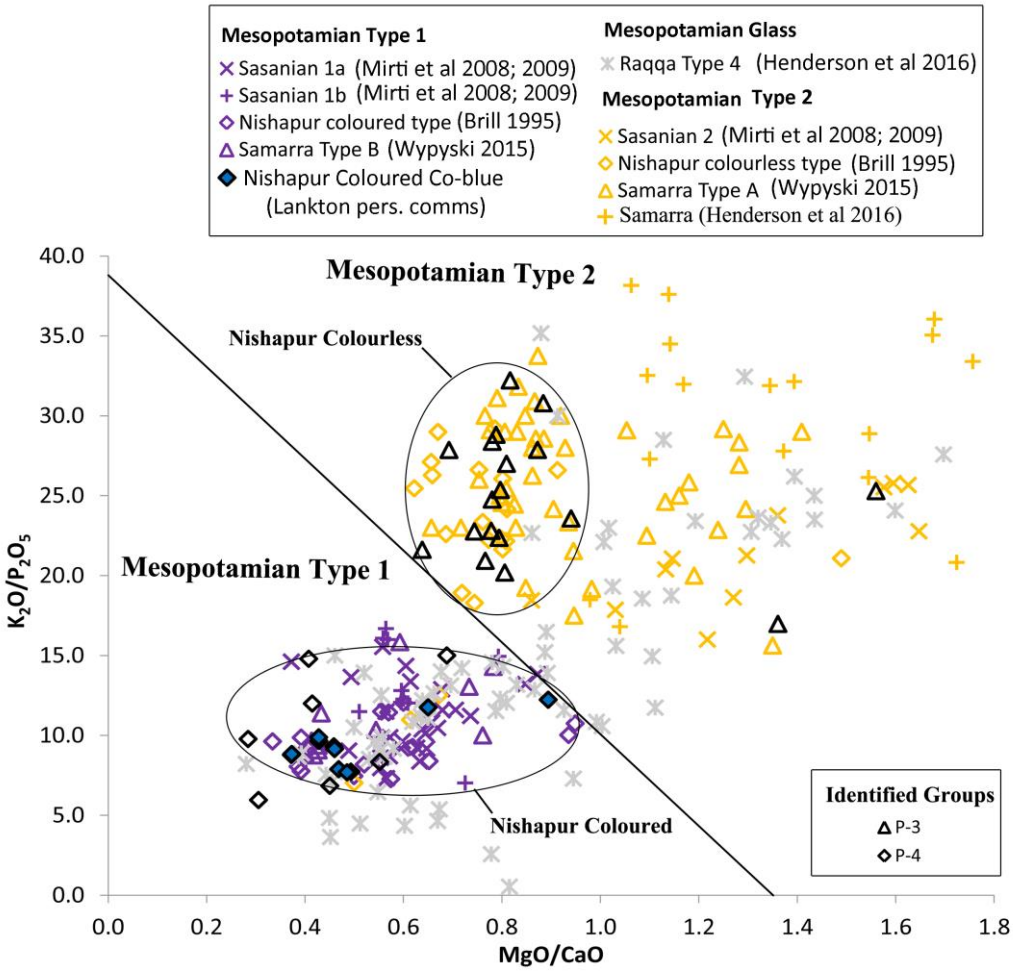


Figure 7.12. The flux content of P-3 and P-4 groups compared against known Mesopotamia glass types. Mesopotamian Type 1 and 2 are marked as identified in Chapter 4. Data sources in key.

Within the Mesopotamian Type 2 group, P-3 indicates closest affinity to the Nishapur Colourless Type (Figure 7.12). Nishapur Colourless forms a lower magnesia cluster within a larger spread of glass of Samarran and Sasanian origins. The Nishapur Colourless and Samarran glass are indistinguishable from the Sasanian 2 group from Veh Ardašīr, suggesting that Islamic glass production in this region was a continuation of Sasanian practice in technology and raw materials. Wypyski (2015, 136) suggests that Samarra was the most likely production site of the Nishapur Colourless glass type (discussed further in Chapter 9). The smaller compositional range implies that the P-3 and Nishapur Colourless groups may represent a sub-set of superior quality glass within Samarran production which may have been preferentially imported to both Palestine and Nishapur.

P-3 has very low Al_2O_3 (av. 1.0%) and extremely low levels of heavy mineral oxides (0.04% TiO_2, 0.42 Fe_2O_3 and ~60ppm ZrO_2). It indicates the use of a very mature sand source with few accessory minerals, or possibly the use of crushed quartz pebbles, as suggested by Brill (1995,). This glass also has a notably high silica content (av. 71%) compared to the other groups (67-69%). Trace elements are also characteristically low, particularly in V, Ga, Nb, Th and U (Figure 7.7a), as is the total REE (22.9ppm), which is the lowest of any glass group. P-3 demonstrates a prominent negative Eu anomaly (Figure 7.7b), which it shares with groups P-2 and P-4. Like other plant ash glasses, manganese oxide was added as a decolourant, although in smaller quantities than the other groups (see later).

Comparison of P-3 with other Mesopotamian glass (Figure 7.13 a & b) alongside circled regions representing compositions from the Levant and Egypt of both plant ash and natron types indicate P-3 to be a very distinct and well constrained group, closely matching that of Nishapur Colourless although with two samples falling into the larger Mesopotamian Type 1 region populated with samples from Samarra and Veh Ardašīr (Sasanian 2). Clear difference is shown with respect to the Mesopotamian Type 1 glass groups. The Mesopotamian Type 2 groups appear to use a purer sand (or pebbles). This does not appear to be a regional distinction as groups of both types are found from the same sites (Nishapur, Samarra, Veh Ardašīr). It might suggest that a choice is

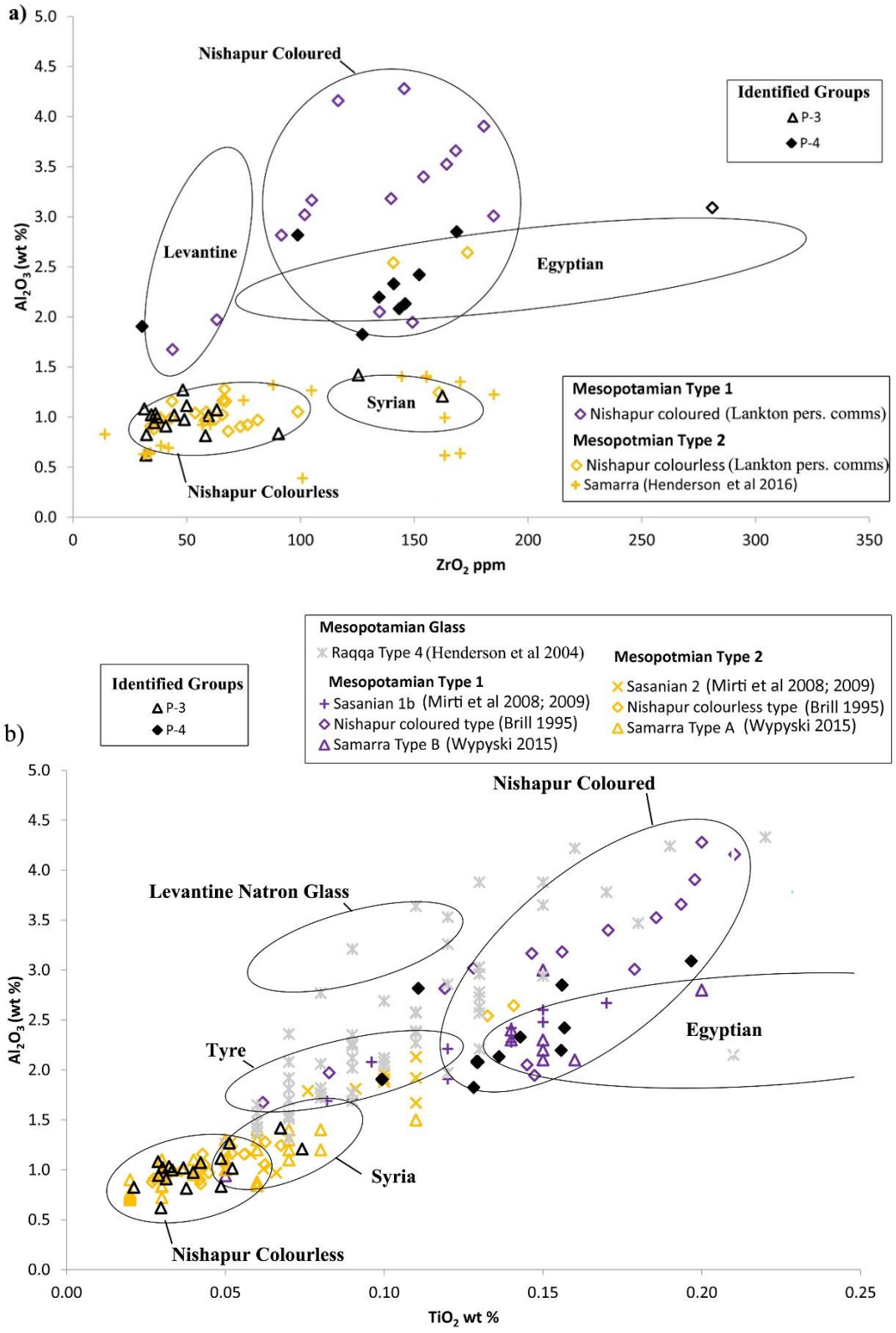


Figure 7.13. a) Al_2O_3 vs. ZrO_2 and b) Al_2O_3 vs. TiO_2 for the P-3 and P-4 groups compared to known Mesopotamian glasses from Nishapur, Samarra, and Sasanian example. In addition, circled areas are marked as in Figure 7.6 (a&b) showing Levantine glass (Bet Eli'ezer, Apollonian, Tyre); Egyptian glass (Egypt II, Group 3A) and Syrian glass (Raqqa Type 1) for comparative purposes. The graphs demonstrate a match between P-3 and the Nishapur Colourless glass and P-4 and the Nishapur Coloured glass.

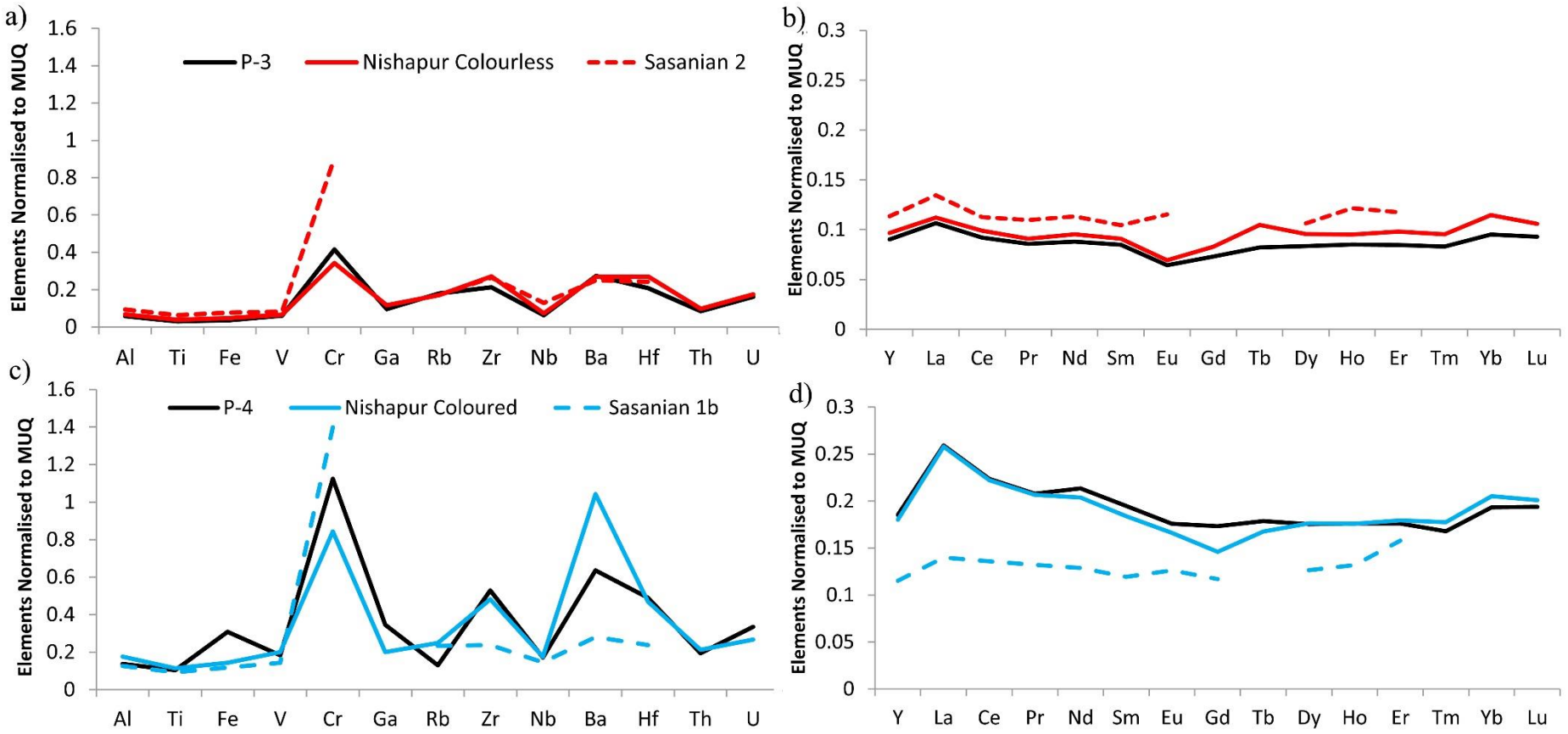


Figure 7.14. A comparison of Groups P-3 and P-4 in selected major, minor, trace and rare earth elements principally related to the silica source for the investigation of mineralogy and geochemistry of the samples. (a) and (b) compare P-3 against other Mesopotamian Type 2 glass. A very low content of both sets of elements is observed, with close similarities in profile shown. (c) and (d) compare P-4 against the Mesopotamian Type 1 glass. Strong similarity is seen toward the Nishapur Coloured glass, which demonstrate a marked agreement, but less so to the Sasanian glass. All elements are normalised to MUQ (Kamber et al 2005).

being made to match certain types of flux with certain types of sand/pebbles, with Mesopotamian Type 2 plant ash being employed with higher quality silica-sources. This is illustrated in the differences in vessels by comparing the superior quality cut glass of Nishapur Colourless to the much wider range of vessel quality of the Nishapur Coloured type (Kröger 1995).

Wypyski (2015, 136) reports that Samarra Type A encompasses a range of glass colours, not just high quality colourless glass. Therefore, a continuum of glass compositions may have been produced at Samarra with different 'grades' of glass selected after firing for different uses. Glass production may have been more variable and less well controlled than that evidenced from the colourless glass groups alone as Palestine and Nishapur may have only imported glass of the higher qualities.

A final comparison was performed using the trace elements (Figure 7.14a) and REE (Figure 7.14b) content of P-3 alongside Nishapur Colourless and Sasanian 2. P-3 and Nishapur Colourless share an affinity, characterised by low concentrations of REE and negative Eu anomalies. Sasanian 2 shares a similar profile to the above groups but lack the negative Eu anomaly and have increased levels of Cr and Nb. It is suggested that while these groups share the same geological origin for their silica sources, P-3 and Nishapur Colourless (and probably Henderson et al's Samarra Group and Wypyski's Samarra Type A) are likely to have been produced in the same production location using the same plant ash and silica sources, while the Sasanian 2 type is similar but separate production.

7.2.3.2 P-4: Nishapur Coloured/Samarra Type B

P-4 is a group of 10 cobalt blue vessels, seven of which are of a specific type of elongated bottle (Figure 7.15). They contain 500-2000ppm CoO and 1500-6500ppm CuO, as well as a very high Fe_2O_3 content (>2%), all of which are probably related to the cobalt additive. This group has a Nishapur Coloured base glass characterised by a mid-range flux content of av. 2.9% MgO, 6.8% CaO, 2.0% K_2O and 0.2% P_2O_5, producing flux ratios of 0.43 MgO/CaO and 9.7 K_2O/P_2O_5. This corresponds to Mesopotamian Type 1 plant ash type (Figure 7.12). There is some overlap with the Eastern

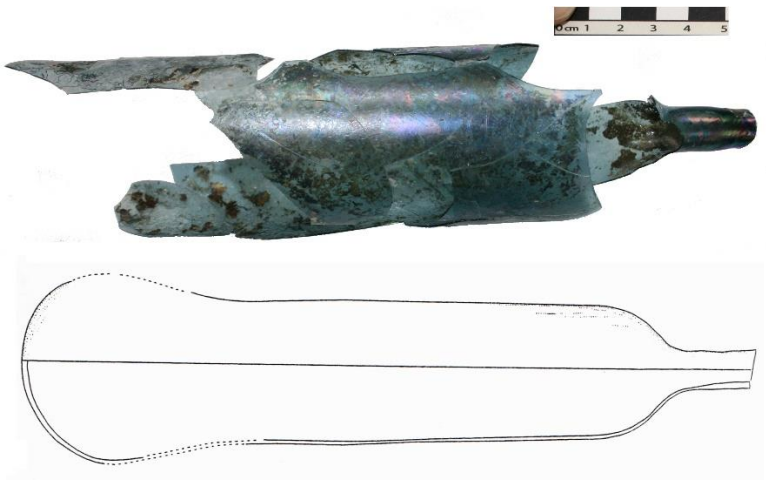


Figure 7.15. Example of an 'elongated bottle' of P-4 composition. It is thin walled and cobalt blue. Sample CEA W2S3-04

Mediterranean glass, due to similarities in MgO, although clear separation is maintained by the CaO content which is universally lower in Mesopotamian glass.

In the original definition of the Nishapur Coloured group by Brill (1995) self-coloured and deliberately coloured glass were included together. In the definition of Nishapur Coloured as presented in this thesis (Chapter 4), only the self-coloured samples were considered. Of the remaining deliberately coloured samples, 8 were coloured using cobalt, and have been designated Nishapur Co-blue and will be used for comparative purposes, the data source is Lankton (pers. comms). Nishapur Co-blue has the same Nishapur Coloured base glass and is also enriched in iron oxide ranging from 1.2-2.7%. The alumina content of P-4 is high and variable (av. 2.4%; s.d 0.43), as are the heavy mineral oxides (0.14% TiO_2, 142ppm ZrO_2) and total REE (53.7ppm), although still generally less than Egypt II glass. In the trace elements and REE (Figures 7.7a & b) the P-4 group demonstrates substantial but variable levels of Cr (av. 105ppm; s.d 51). High Cr is noted as a characterisation of Mesopotamian glasses of Late Bronze Age dates (Shortland et al 2007), however the content in P-4 is much higher than the 10-20ppm reported by Shortland et al (ibid, 784). P-4 also exhibits pronounced amounts of Ba, Hf, Th, U, Ga and V and a slightly negative Eu anomaly, similar to P-3.

Cluster analysis identified P-4 as a single group, but with a large compositional spread in some elements, for example in Al_2O_3, TiO_2 and ZrO_2 compared with P-1, the Tyre type glass (see Table 7.1). This large spread is readily visible in Figures 7.13a & b with

P-4 and Nishapur Coloured creating a diffuse cloud of samples. This is in contrast to the Sasanian 1b group, which appears to have used similar raw materials, but which has a much more restricted compositional spread. The wide compositional range of P-4 suggests this type might be more than one production group. Figure 7.17 presents Al_2O_3/TiO_2 against Al_2O_3/ZrO_2 for P-3 and P-4 and the Mesopotamian comparative groups, which also includes the Nishapur Co-blue group. Using a ratio-ratio plot some of the groups can be isolated. The image demonstrates that the groups within the Mesopotamian Type 2 flux form a close cluster. Similarly, most of the glass of Mesopotamian Type 1 also form a cluster, going some way to confirming that P-4, Nishapur Coloured and Nishapur Co-blue are indeed productions from a similar region. However, 3 samples of Nishapur Co-blue and 1 sample of P-4 are found to the far right hand side of the image, these possibly represent a compositional sub-group from a different region using different sands. Sasanian 1b, likewise, is separate, indicating a different sand source and production region.

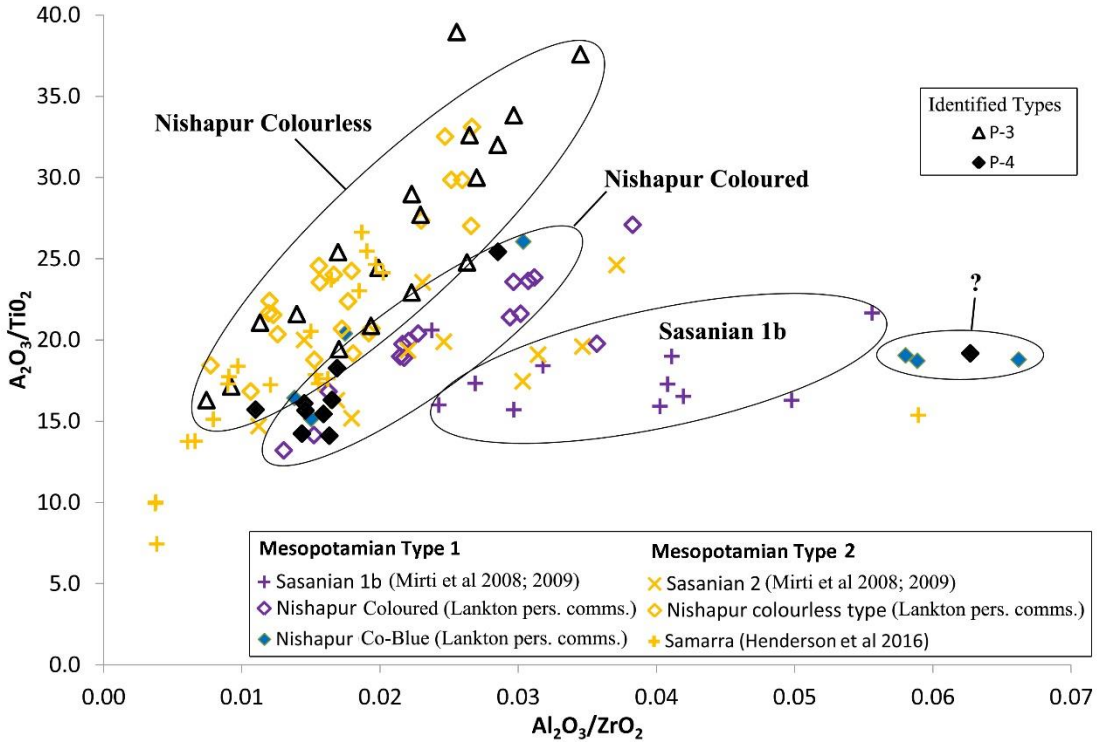


Figure 7.16. Ratio-ratio graph of the feldspar/rutile and feldspar/zircon mix of the sands. The Mesopotamian Type 1 and Mesopotamian Type 2 groups are shown to use similar sand types for their respective groups except for Sasanian 1b. A further separate sub-group of 4 samples is shown to the far right of the image.

A final set of comparisons are made to the trace and REE values in Figures 7.14 (c&d). P-4 and Nishapur Coloured share a prominent resemblance in REE profile and in certain trace element abundances (Hf, U, Ba, Zr, Cr and V), further confirming their compositional affinity and common production region.

7.3 The Outliers

During statistical analysis, nine samples were classified as outliers. An absence of colourant elements, which are proxies for recycling, in all samples except three (CEA 6194-01, CEA 6194-05, HB 3032-20) imply that many of the outliers represent minor compositional types rather than types altered by recycling or mixing. The outliers are identified individually in Appendix J and are presented in Figures 7.17 (a & b) with each labelled.

HB 3032-06 and HB 3032-20 were identified as most typical to Tyre glass, although the alumina contents of both is lower than would be typical. HB 3032-20 has elevated Cu and Pb which might indicate recycling. HB 3032-06, on the other hand, is cobalt blue and contains CoO (354ppm), CuO (902ppm) and high Fe_2O_3 (1.23%). This sample is therefore identified as a cobalt coloured Tyre type, and is designated P-1 Co-blue.

BSH 2885-09 and BSH 2885-10 match the P-2b group closely, the only difference being a slightly low alumina content. They also share the dating and location of other P-2b samples, and so are probably of this group.

CEA 6194-01 and -05 are unknown types with an Eastern Mediterranean flux signature. They show no close similarity to any of the presented groups.

TR 6055-02 is potentially a Raqqa Type 4 glass, although the similarity is not exact. It has high amounts of MgO, similar to Mesopotamian glass, but high lime (~10%), which is more typical to Eastern Mediterranean glasses but is also found in Raqqa Type 4 in up to 9%. This identification is also supported by the silica source elements.

Similarly, AY 2989-08 and RAM 5947-17 are also Mesopotamian Types, with their flux suggesting Mesopotamian Type 2. The former contains much higher Al_2O_3 then other

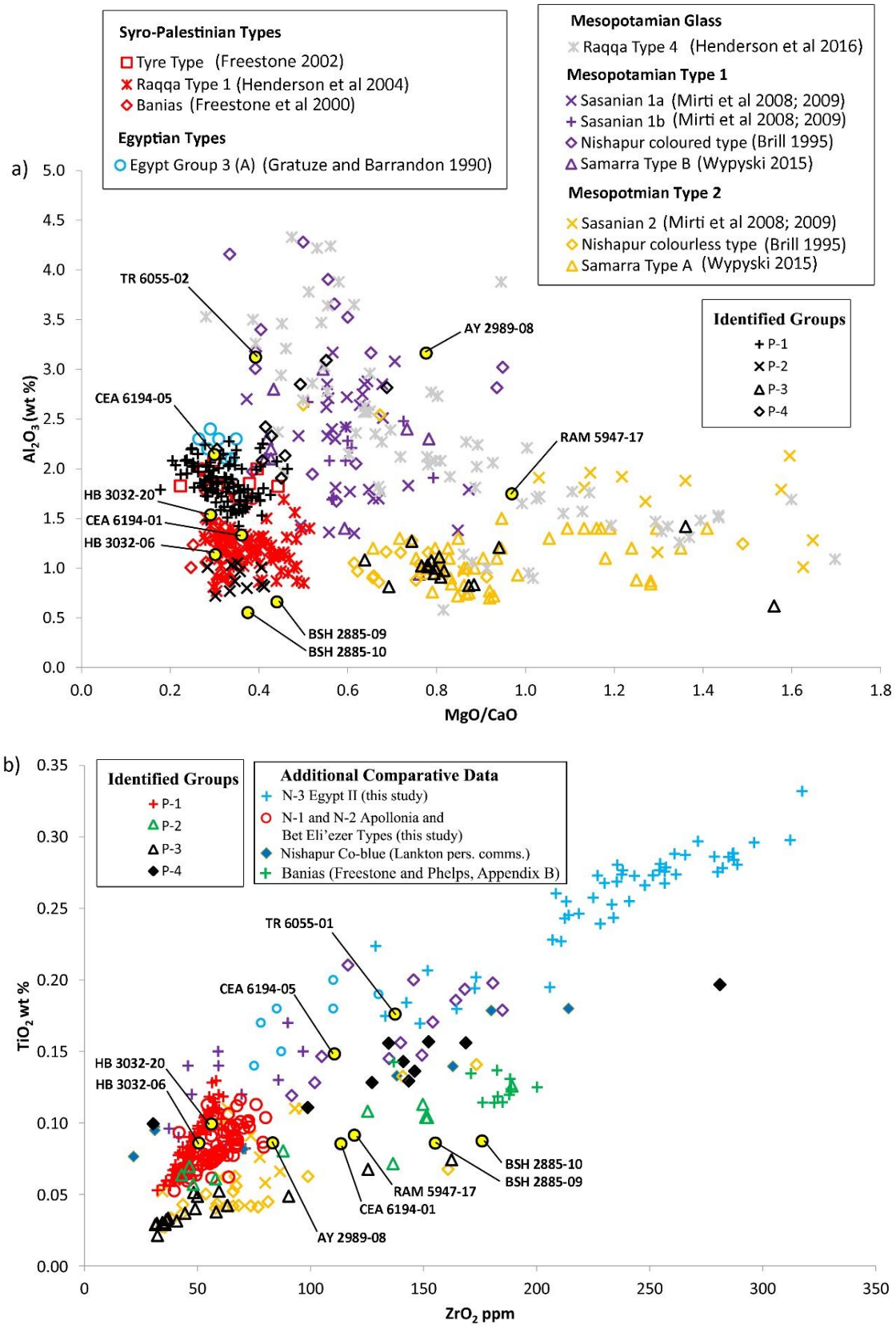


Figure 7.17. Nine outlier samples plotted against comparative data and the identified groups. (a) Al_2O_3 vs. MgO/CaO and (b) TiO_2 vs. ZrO_2. Outlier samples are individually labelled.

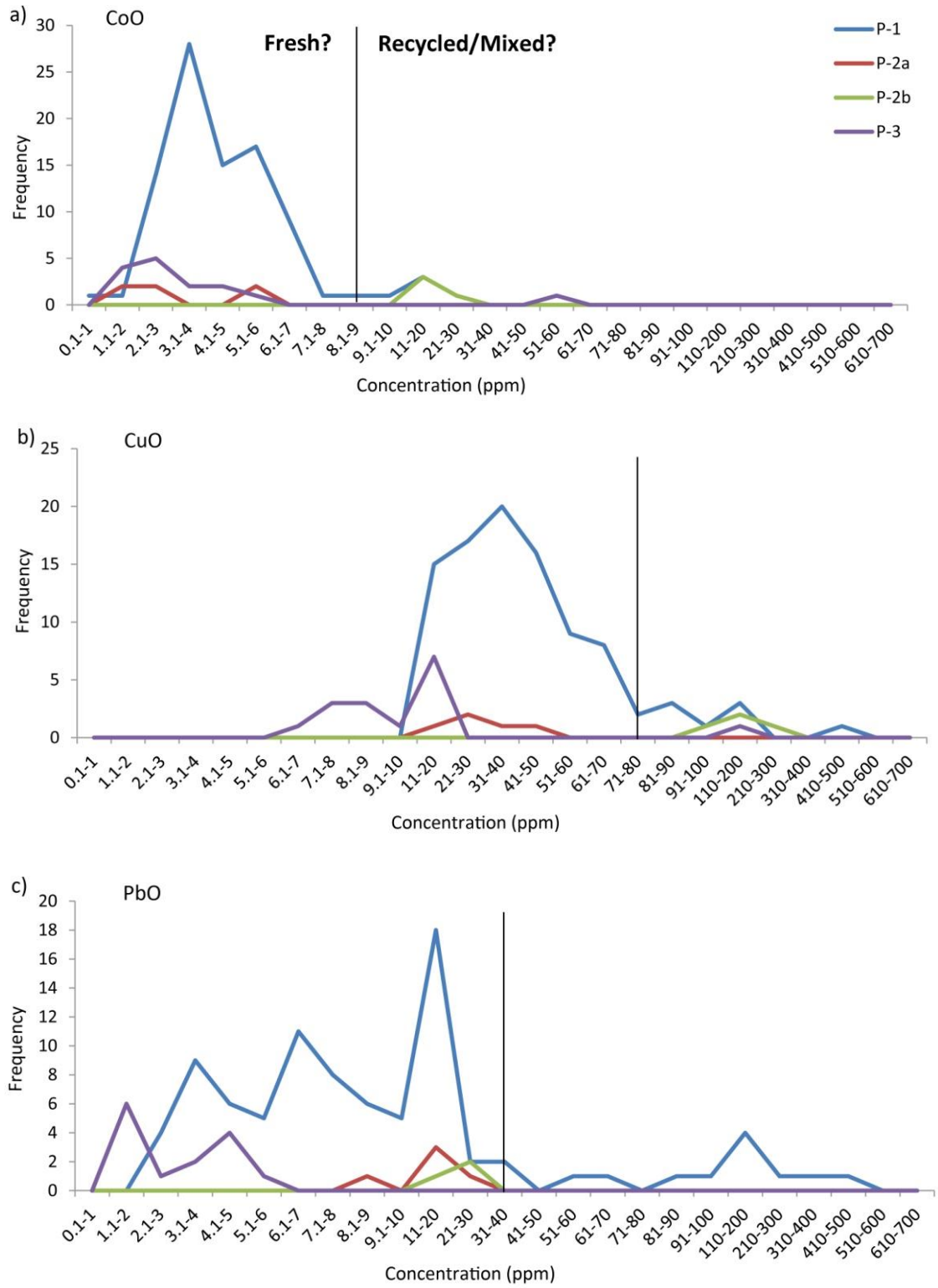
Mesopotamian types and is an unknown production. The latter sample could be either a Nishapur Colourless type or also Raqqa Type 4.

7.4 Recycling

Figure 7.18 (a-c) presents frequency of vessels versus their content of CoO, CuO and PbO, which can be used as proxies for recycling. As discussed in Section 6.6, it was reasoned that the threshold between the geological background level of a particular component and incidental addition due to recycling most probably lies just above the peak in the distribution. Thus, in each image the geological level is estimated using a black line and concentrations of colourant above this are assumed to be recycled. As before, recycling is defined as primarily the addition of quantities of cullet to a batch of fresh glass rather than 100% recycled material, although it is also possible that that was occurring. MnO was not utilised in this investigation due to its routine application as a decolourant in plant ash glass. Groups P-1, P-2 (a & b) and P-3 are presented but Group P-4 was omitted as these samples are deliberately coloured.

Background levels for CoO are suggested at 8ppm (Fig. 7.18a) for all the glass groups except for P-2b which contained 10-30ppm CoO. This is higher than typically reported for plant ash or sand (Brems and Degryse 2014; Barkoudah and Henderson 2006) and might suggest that this group is 100% recycled glass although it might also suggest a sand or plant source with an anomalously high CoO content.

The CuO concentration is more variable; P-3 has the lowest levels at <30ppm, P-2a <60 and the vast majority of P-1 <80ppm, with values above this suggesting recycling. This level is high, around a magnitude larger than the natron glass, estimated at <8ppm. Typical contents in plant ash are recorded, depending on species (and most likely also location), at between 12-105ppm (Barkoudah and Henderson 2006, 307), however considering that plant ash makes up no more than one quarter of the glass raw materials by weight, the plant ash alone is insufficient. Nonetheless, comparison to chunk and waste glass analysed from the primary production site at Tyre (see Appendix B) indicates an average CuO content of 68ppm, ranging from 24 to 89ppm



Figures 7.18. Line graphs demonstrating vessel frequency against oxide concentration for three colourant elements; a) CoO, b) CuO and c) PbO. Concentration are in ppm using a log scale. These images investigate the geological levels of each oxide in the glass samples. The black line indicates an estimate for the background level, left of this fresh glass is expected, right of this recycled is supposed.

(not including the coloured sample). This suggests that either the plant ash glass from Tyre had particularly high levels of CuO in the raw materials, or that cullet was being added in the primary stage. Note that P-2b also presents an anomaly with CuO contents of around 100-300ppm.

For PbO, background levels are around <40ppm in all groups apart from P-3 which has a lower level of <8ppm. This is similar to that reported in plants (ibid) and broadly similar to that reported from Tyre (Appendix B), although the content at from Tyre appears to be quite variable.

In assessing these results, values of around <8ppm CoO, <80ppm CuO; <40ppm PbO can be used to define a background geological content of the glass, consequently facilitating the estimation of fresh and recycled glass. These values seem to be quite high but considering the analysed glass from the primary production site at Tyre, these values appear, at this time, to be within the concentrations of fresh plant ash glass. Therefore, using these values, 20% of P-1 contained colourants above this estimated geological level, none of the samples of P-2a and a single sample of P-3 (5%; CEA 6194-10). This latter sample is a distinctive blue colour (Figure 7.19) and might instead be deliberately coloured, although colourant levels are quite low (55ppm CoO; 183ppm CuO). The P-2b group of 6 vessels appears to either be 100% recycled or signal that the raw materials present were abnormally high in colourant elements. At this juncture the status of this group is unknown and will not be included in the further investigation below. It is noted by Barkoudah and Henderson (2006) that plants uptake colourant elements well, and it might be that the colourant content of plant ash varied widely between different locations.

Figure 7.19. Blue colouration of CEA 6194-03.

Table 7.7. Mean and standard deviation for the P-1F (fresh) and P-1R (recycled) groups. Values in wt % unless otherwise stated. bdl = Li_2O, Cd, In, Au, Pt, Se and Sb_2O_5. Eu = Eu Anomaly.

Major, Minor, selected trace oxides

Group	N	Colour*		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO	CoO†	CuO†	PbO†	Total Col‡
P-1F	82	Colourless	M	12.43	3.01	1.84	68.04	0.30	0.78	2.53	9.36	0.08	0.48	1.00	4	37	9	50
			S.D	1.13	0.48	0.19	1.72	0.06	0.11	0.36	1.15	0.02	0.11	0.35	1	15	6	18
P-1R	20	Light bluish-green	M	12.21	3.04	1.96	67.40	0.32	0.73	2.57	9.95	0.09	0.60	0.96	13	94	109	216
			S.D	0.78	0.61	0.19	1.47	0.05	0.09	0.33	1.16	0.02	0.10	0.47	15	94	124	176

Trace oxides in ppm

Group	B_2O_3	V_2O_5	Cr_2O_3	NiO	ZnO	GaO	As_2O_3	Rb_2O	SrO	ZrO_2	Nb_2O_3	MoO	Ag	SnO_2	Cs_2O	BaO	HfO_2	Ta_2O_3	WO	Bi	ThO_2	UO_2
P-1F	259	21	21	10	39	3.5	3.0	17	669	47	2.0	3.0	0.05	3.1	0.14	281	1.04	0.10	0.27	0.01	0.94	0.50
	33	4	17	2	10	0.6	0.9	2	139	6	0.4	1.0	0.03	4.3	0.05	48	0.14	0.02	0.12	0.01	0.12	0.11
P-1R	254	23	18	12	46	3.7	3.4	17	688	52	2.2	2.8	0.52	11.1	0.11	286	1.13	0.11	0.25	0.02	1.03	0.56
	34	5	5	2	12	0.5	1.1	3	95	7	0.4	1.4	1.34	9.8	0.06	49	0.16	0.02	0.11	0.02	0.12	0.10

REE Oxides in ppm

Group	Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu	La/Yb	Total REE
P-1F	7.62	7.37	13.40	1.72	6.97	1.40	0.36	1.22	0.19	1.11	0.23	0.61	0.08	0.58	0.08	0.28	12.74	42.98
	1.02	0.72	1.62	0.18	0.77	0.17	0.05	0.18	0.02	0.14	0.03	0.08	0.01	0.07	0.01	0.02	0.96	4.72
P-1R	8.27	7.75	14.01	1.81	7.20	1.45	0.38	1.32	0.21	1.18	0.25	0.66	0.09	0.63	0.09	0.28	12.48	45.28
	1.05	0.75	1.29	0.13	0.50	0.12	0.04	0.10	0.02	0.12	0.03	0.08	0.01	0.06	0.01	0.02	0.99	3.89

* = most frequent vessel colour; † = in ppm; ‡ = PbO+CuO+CoO

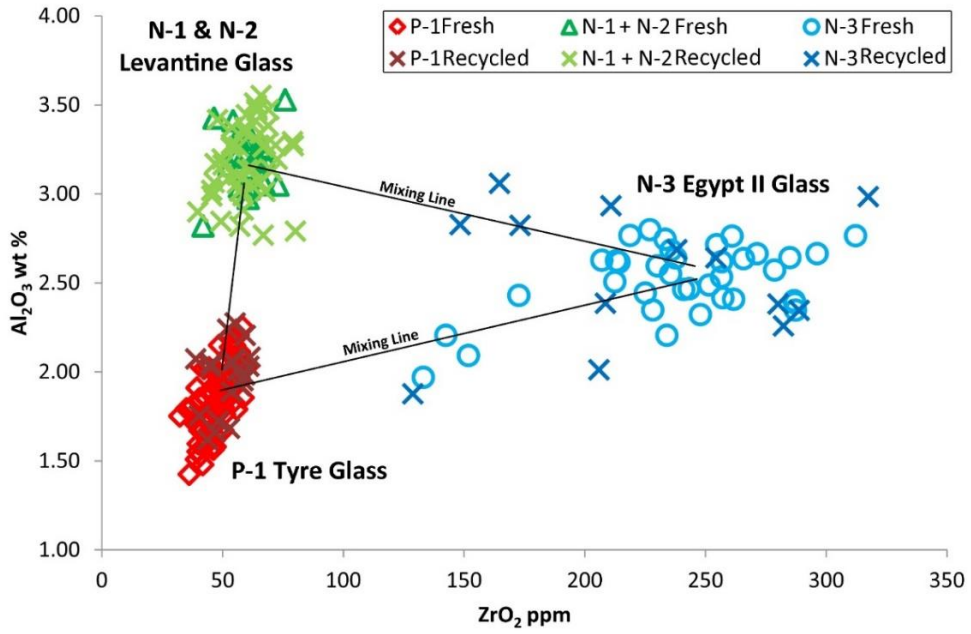


Figure 7.20 Investigation of mixing between the three largest glass types: N-1 + N-2 (Levantine Natron glass), N-3 (Egypt II Type) and P-1 (Tyre Type Glass). For each type the Fresh and Recycled vessels are denoted. Mixing lines are drawn between the groups.

Table 7.7 presents the mean and standard deviation of the P-1 glass considered 'fresh' (P-1F) alongside that of the glass considered 'recycled' (P-1R). Unlike the natron recycled glasses, there appears to be no significant correlation between higher flux content and recycling. This might be because the furnace atmosphere during re-melting has a lower impact than the natural variations in the plant ash raw materials. Nonetheless, comparing the averages for the fresh and recycled P-1 groups, very slight increase in P_2O_5 and K_2O and MgO is visible in the recycled glass, which may be consistent with contamination during re-melting. Larger increases are also evident in CaO at around 0.6% in the recycled glass. However, none of these increases extend beyond 1σ and cannot be described as significant.

Mixing between the dominant glass groups is investigated in Figure 7.20. The combined samples of N-1 and N-2 represent Levantine glass, N-3 as Egypt II glass, and P-1 as Tyre glass. The mixing lines between the groups have been approximated and for each group the 'fresh' and 'recycling' examples have been identified.

Three trends are observed: i) mixing between the Levantine glass and Egypt II; ii) mixing between the glass from Tyre and Egypt II (both trends were noted in Chapter

6); and iii) that there is no identifiable mixing between the Tyre and Levantine glass. Although most of P-1R border the main cluster towards the Levantine and Egyptian groups. This might suggest that Tyre glass was being mixed mainly with itself, and if mixing outside the group was occurring, it was only small quantities of natron glass being added to a much larger body of Tyre glass, but not in significant quantities to make a difference to overall composition. It suggests that the Tyre glass comprised the bulk of glass in circulation during its stage of use. Although, it might also imply that strict vessel sorting was being performed, particularly if clear colourless glass was in demand, as it was in the Abbasid period (Baker 2004).

7.5 Colourants and Decolourants

7.5.1 Cobalt-Blue Vessels

A total of 11 plant ash glass samples were deliberately coloured using cobalt; 10 of these formed P-4 and a single sample, first identified as an outlier, forms P-1 Co-blue. They have Nishapur Coloured and Tyre base glass respectively. In addition, 3 cobalt blue natron glasses were identified in Chapter 6, these are N-3 Co-blue, with an Egypt II base glass. All of these groups will be investigated here.

Table 7.8 compares average values of 9 colourant elements for the three groups (N-3 Co-blue; P-1 Co-blue; P-4) alongside their base glasses (N-3F, P-1F and Nishapur Coloured) and also against literature cobalt-blue vessels of the same base glass. These are a group 11 ‘Scratch Decorated’ vessels (Brill 1999A, 96; 1999B, 194-5) which share the composition of typical Egypt II glasses, here designated Egypt II Co-blue; one sample of co-blue glass from the production site of Tyre (Phelps and Freestone, see Appendix B); and a group of 8 Nishapur Co-blue samples analysed by Lankton (pers. comms.). (Details of the comparative data can be found in Table 7.4). The values are presented against their base glass in Figure 7.21 (a-c). Finally, Figure 7.21 d) presents all of the cobalt coloured groups so that cross-comparisons can be made.

Table 7.8. Selected oxides for the cobalt glasses compared to literature cobalt glass groups and their base glass. All in ppm. Cobalt coloured glass shaded in blue, base glass un-shaded. N-3 = Egypt II, P-1 = Tyre, P-4 = Nishapur Coloured.

	N	Fe_2O_3	MnO	CoO	Ni O	CuO	Zn O	As_2O_3	SnO_2	PbO
N-3 Fresh	37	9317	195	3	7	3	18	2	8	4
N-3 Co-blue	3	14192	2972	589	16	1006	691	4	8	235
Egypt II Co-blue[1]	11	14972.73	140	700	10	1900	2300	n/a	40	650
P-1 Fresh	82	4788	10047	4	10	37	39	3	3	9
P-1 Co-blue	1	12297	4631	354	24	902	655	9	21	539
Tyre Co-blue[2]	1	32788	8164	810	28	2562	591	15	14	48
Nishapur Coloured[3]	15	11161	3871	10	41	69	51	18	18	114
P-4 (all Cobalt blue)	10	23932	12499	1257	273	3987	740	22	28	227
Nishapur Co-blue[3]	8	18014	11724	797	182	2101	346	17	24	142

[1] Selected natron scratch decorated samples, Brill 1999B

[2] Data Freestone and Phelps, Appendix B

[3] Lankton pers.comms.

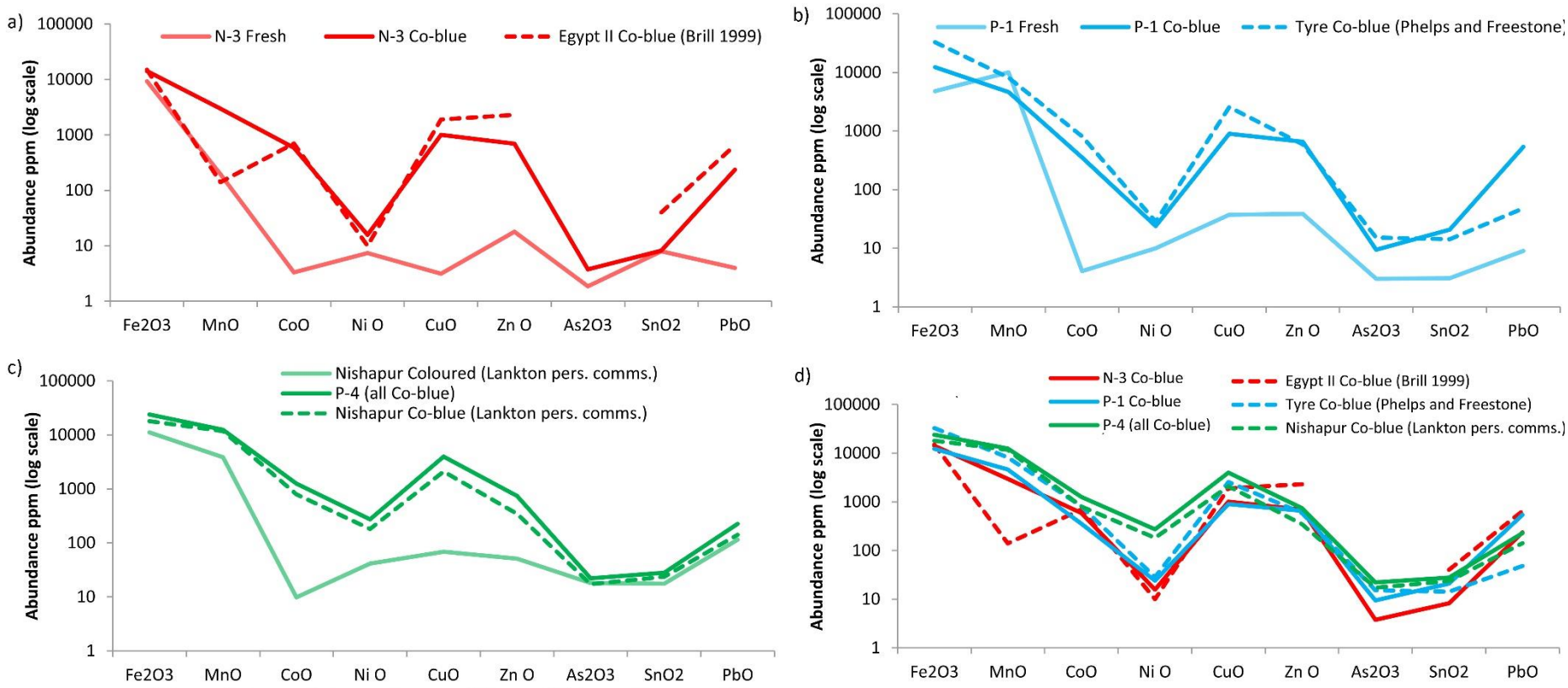


Figure 7.21. A comparison of the cobalt glasses against base and literature co-blue groups. Graphs are grouped by base glass: a) Egypt II glass; b) Tyre type glass; c) Nishapur Coloured glass. d) is a cross-comparison of all the cobalt glass types. The oxides iron, nickel, copper, tin and lead appear common to all the cobalt glass groups, but group differences are also noted: P-4 with higher NiO; P-1 with increased SnO_2; and Egypt II Co-blue with additional ZnO.

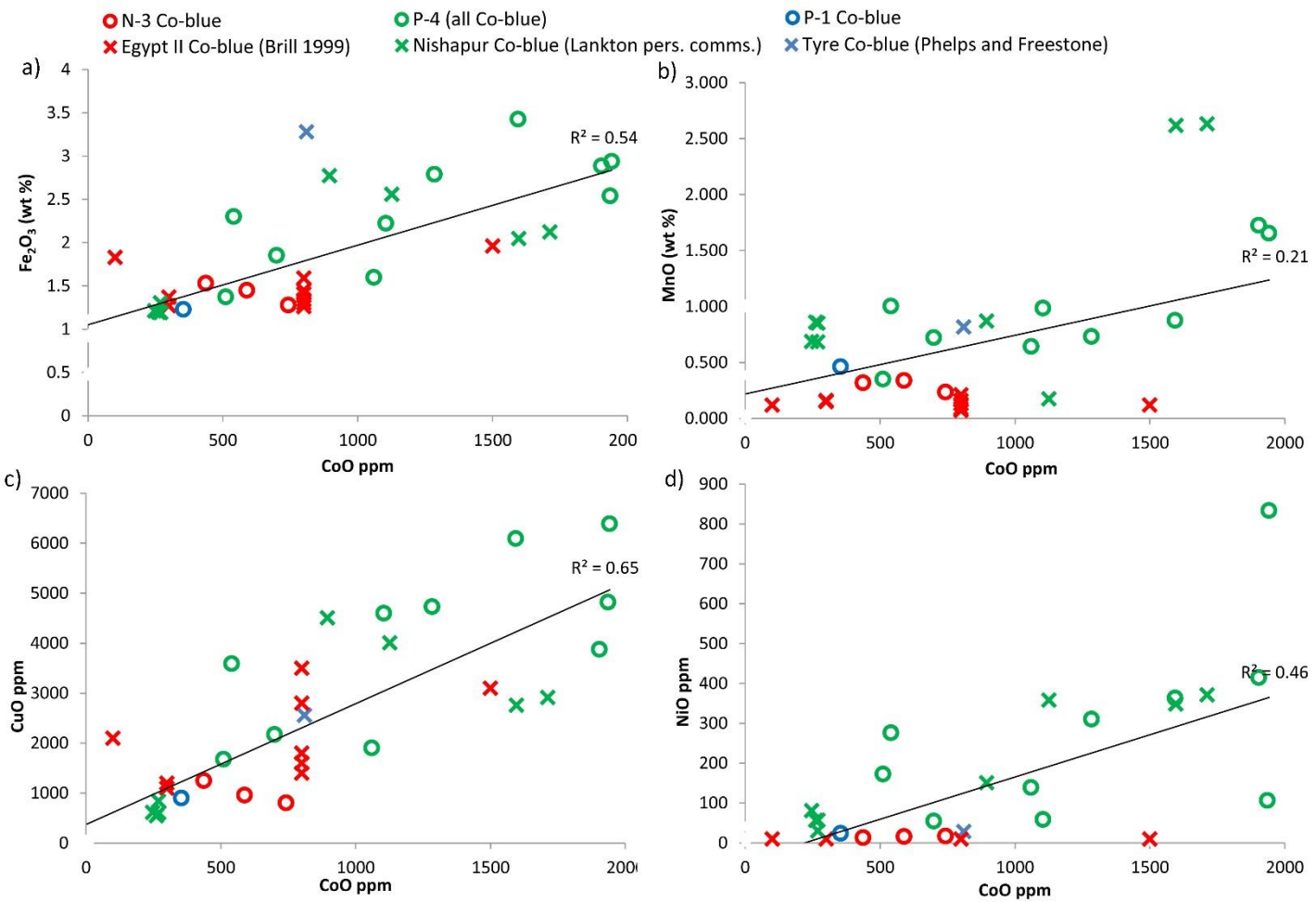


Figure 7.22 (a)-(d) presents the correlation between selected oxides and cobalt. Identified groups are circles, comparative data are crosses. Colouration is by base glass. The trend line is for all the data points. Weak correlations are seen for all the oxides, with the best correlations visible in the P-4 and Nishapur Co-blue groups. Lead and zinc demonstrated very low correlations and are not presented. Different cobalt additives are suggested for each base glass.

These figures demonstrate several trends; all the cobalt coloured glass contains elevated oxides of iron, nickel, copper, zinc and lead (see Table 7.8) but there were also some regional differences. The cobalt glasses of a Nishapur Coloured base were rich in nickel and manganese; Brill's Scratch decorated glass (Egypt II Co-blue) had much higher amount of zinc, but this was not shared by N-3 Co-blue, which in turn had raised manganese oxide, while the samples of Tyre glass had increased tin oxide at around 10-20pm, and also possibly manganese oxide.

Correlations between cobalt and iron, manganese, copper and nickel oxides are presented in Figure 22 (a-d). The highest correlation with cobalt is seen in iron and copper, R^2 = 0.54 and 0.65 respectively, with the values representing all the vessels. The best correlation is visible in the samples of Nishapur Coloured base glass. A stronger correlation is seen between the oxides of copper and iron (r^2=0.77), suggesting possibly more than one component to the cobalt additive, probably due to natural variations in the ore. In all the cobalt blue samples, iron is present at approximately 0.5-2.5% above the means of the respective base glass and copper at between 600-6500ppm. Lower correlations are seen in MnO (r^2=0.21) and NiO (r^2=0.46), both of which are raised in Nishapur Coloured base glass which contains between 50-800ppm nickel and around 0.8% higher amounts of MnO. MnO is also increased in N-3 Co, but by a much smaller quantity of around 3000ppm. In the Tyre glass, quantities of MnO fall beneath that of the base average, however this is probably due to less MnO being added as a decolourant, and so MnO in the cobalt ore cannot be ruled out.

No correlation was seen in ZnO overall, although a correspondence has already been noted for N-3 Co (see Chapter 6), but the small sample size makes any potential conclusions unreliable. Seven samples of Brill's scratch decorated glass (Egypt II Co-blue) contain much higher quantities (~800-5000ppm ZnO) than the other glass (mainly <1000ppm), although it must be noted that Brill (1999B) was operating close to the detection limits of his technique. Nonetheless, the scratch decorated samples appear to have used an ore source with a distinctly high zinc content, which was different from the low zinc source used for the N-3 Co group, but which was higher in manganese oxide. As both involved the same base glass, it might be suggested that

cobalt was added at the secondary, rather than primary, production stage, or that cobalt source varied. There is no correlation with lead oxide, whose content appears to vary extensively in the samples.

In summary, 4 different types of cobalt additive were identified, which correspond to base glass, apart from the samples of an Egypt II base glass, in which Brill's (1999B) samples and those analysed here, used cobalt ores of different origins. All samples contained high quantities of iron and copper oxides, but also manganese oxide except for Brill's Egypt II Co-blue group. The co-blue glass of Nishapur Coloured base contained significant amounts of nickel and manganese; the Egypt II Co-blue analysed by Brill (1999) had high quantities of zinc; and the Co-blue glass of Tyre base had slightly raised tin and possibly manganese, along with N-3 Co, which also had increased manganese. It suggests that Egypt, the Levant and Mesopotamian each used slightly different, but also very similar, cobalt types.

There are few published articles that deal directly with cobalt use in Islamic glass (Henderson 2003). Work on Bronze Age Egyptian (Kaczmarczyk and Hedges 1983; Kaczmarczyk 1986; Smirniou and Rehren 2013; Tite 2011; Abe et al 2012; Shortland et al 2006B; Rehren 2001) and Mesopotamian (Neumann 1927; Sayre 1964; Walton et al 2012) objects essentially divide cobalt additives into Egyptian and Mesopotamian sources. Further sources have been identified from later periods coming from Germany, but they are not of relevance here (see Gratuze et al 1995; 2013).

The cobalt additives of New Kingdom Egypt were dominated by a cobalt rich alum source from the Great Western Oases. This contained elevated amounts of Al, Mn, Ni, Zn and Fe (Kaczmarczyk and Hedges 1983; Kaczmarczyk 1986; Shortland et al 2006). Recent work (Shortland et al 2006B; Smirniou and Rehren 2013; Abe et al 2012) has identified additional cobalt variants in Egyptian glass, including a CoCu type. The lack of enrichment in Ni and Al in samples from this study rule out a Western Oases Egyptian source.

Late Bronze Age glass analysed from Nippur in Mesopotamia (Walton et al 2012) presented a different suite of elements, variously high in Pb, As and Sb, and are consequently also ruled out as a source, although similarities in iron oxide and copper

content are evident. The high iron oxide contents led Walton et al (2012) to suggest a cobalt source associated with the minerals jarosite or limonite.

Abe et al (2012) identified and characterised a number of cobalt types in later dated Egyptian glass. In particular, their N2 Type, which was in use during the Ptolemaic/Roman period, is distinguished by particularly high iron, manganese (~1000-8000ppm), copper (~1000-3500ppm), zinc (~80-150) and traces of Ni and Sn. This group forms the nearest match to the groups described here, although lacking the nickel seen in the Nishapur Co-blue glass. Abe et al identified the N2 cobalt group to be most likely from the ancient mines at Qamser near Kashan, Iran (2012, 1797). This site contains a number of cobalt ores, such as erythrite (hydrous cobalt arsenate) and asbolane, a cobalt containing manganese mineral (Kaczmarczyk 1986; Kaczmarczyk and Hedges 1983, 53). Asbolane contains Co and Mn, but also quantities of Ni, and furthermore, is often found in deposits surrounded by other minerals, such as Cu, Fe and Ni (ibid). It can also be associated with amounts of barium and potassium. The associated materials may well explain the concentrations of Cu, Zn, Fe and Ni observed in the samples, and also the correlation between Cu and Fe observed. Therefore, at present the cobalt utilised in cobalt-blue glass described here is of closest match to the asbolane deposits described from Iran for three of the glass types: P-4 (Nishapur Coloured), P-1 Co-blue (Tyre-type) and N-3 Co-blue (Egypt II). A lack of manganese in Brill's Scratch Decorated Samples (Egypt II Co-blue group) suggests an unknown alternative source for this group.

7.5.2 Manganese Oxide Decolourant

Manganese oxide was used in most of the plant ash glasses, principally as a decolourant, although a few purple coloured vessels are also present. Figure 7.23 presents vessel frequency against manganese oxide concentration demonstrating that most vessels have MnO concentrations >0.2%, which is the approximate background level in the raw materials as established from the sand (Brems and Degryse 2014) and plant ash (Barkoudah and Henderson 2006). Only 7 samples, 5 from P-2a and 2 from P-1, provided levels below this.

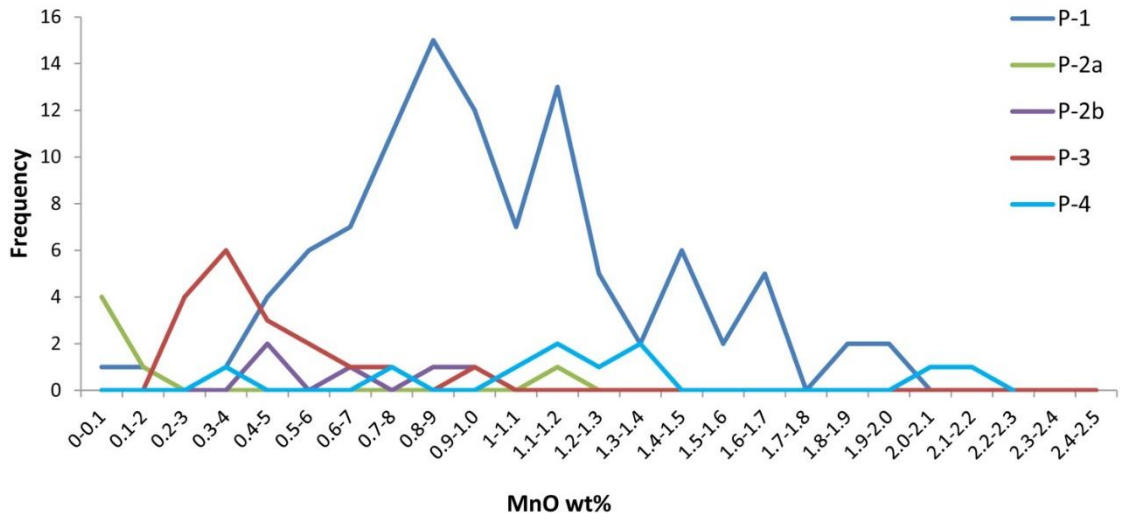


Figure 7.23. Vessel frequency against MnO concentration. Log scale as wt %. Samples are sorted by compositional group.

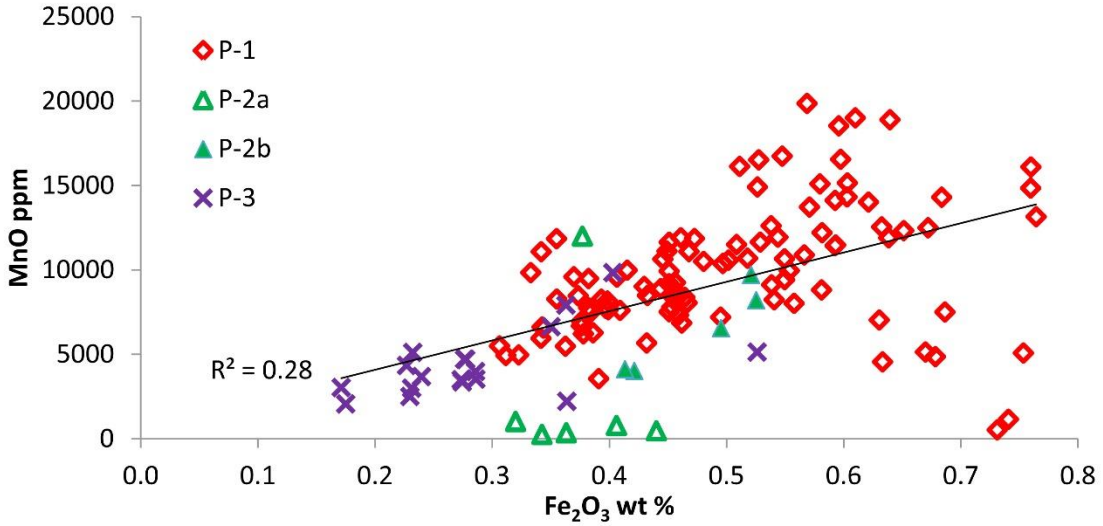


Figure 7.24. Manganese oxide against iron oxide. Trend line includes all the presented data. Numerically, the correlation is weak when including all the samples, however, a rough increase in manganese oxide with iron oxide is identifiable visually within most of the P-1 group, except at the highest concentrations of iron oxide.

There is a reasonable amount of variation between the groups. P-3 and P-2b contain manganese in relatively low quantities: ~0.2-0.8%, while in P-1 the spread is 0.5-2.3%, with most vessels containing 0.8-1.3%. MnO is also roughly positively correlated with iron oxide in the P-1, P-2b and P-3 glass groups (Figure 7.24). This suggests that MnO was added to counteract iron oxide in the glass, presumably as a response to the visual

appearance. P-3, with the smaller amounts of Fe_2O_3, had less added, and P-1, with higher Fe_2O_3, had more. However, there is a group of around six P-1 glasses with MnO contents lower than iron oxide levels would suggest. The colouration of these vessels were mainly pale blueish-greens indicating that they were not adequately decolourised.

Figure 7.25. Four vessels with purple colouration. Clockwise: TIB 5583-11; HB 3032-16; CEA 6194-02 and RAM 5947-28.

Four samples had purple tints (Figure 7.25). They do not show any compositional differences from the other coloured glasses, i.e. their MnO contents are not elevated above those vessels of similar Fe_2O_3 concentration. Therefore, colouration, if deliberate, was achieved by varying the atmospheric conditions within the furnace only. The process of colouration can be further investigated by examining CEA 6194-02. This was a bi-chrome vessel with a purple lower section and a colourless upper section. Both were analysed, the colourless glass as 2A and the purple glass as 2B

(Appendix J). The glasses are extremely close compositionally, however, the purple coloured glass contained 1000ppm more MnO, as well as an increase of 0.08% Fe_2O_3 and 0.6% CaO. These variations are greater than analytical error, suggesting that while the same base glass was utilised, they represent two different batches, although neither glass appears to be specially selected for either role, but simply that one had their furnace conditions marginally altered.

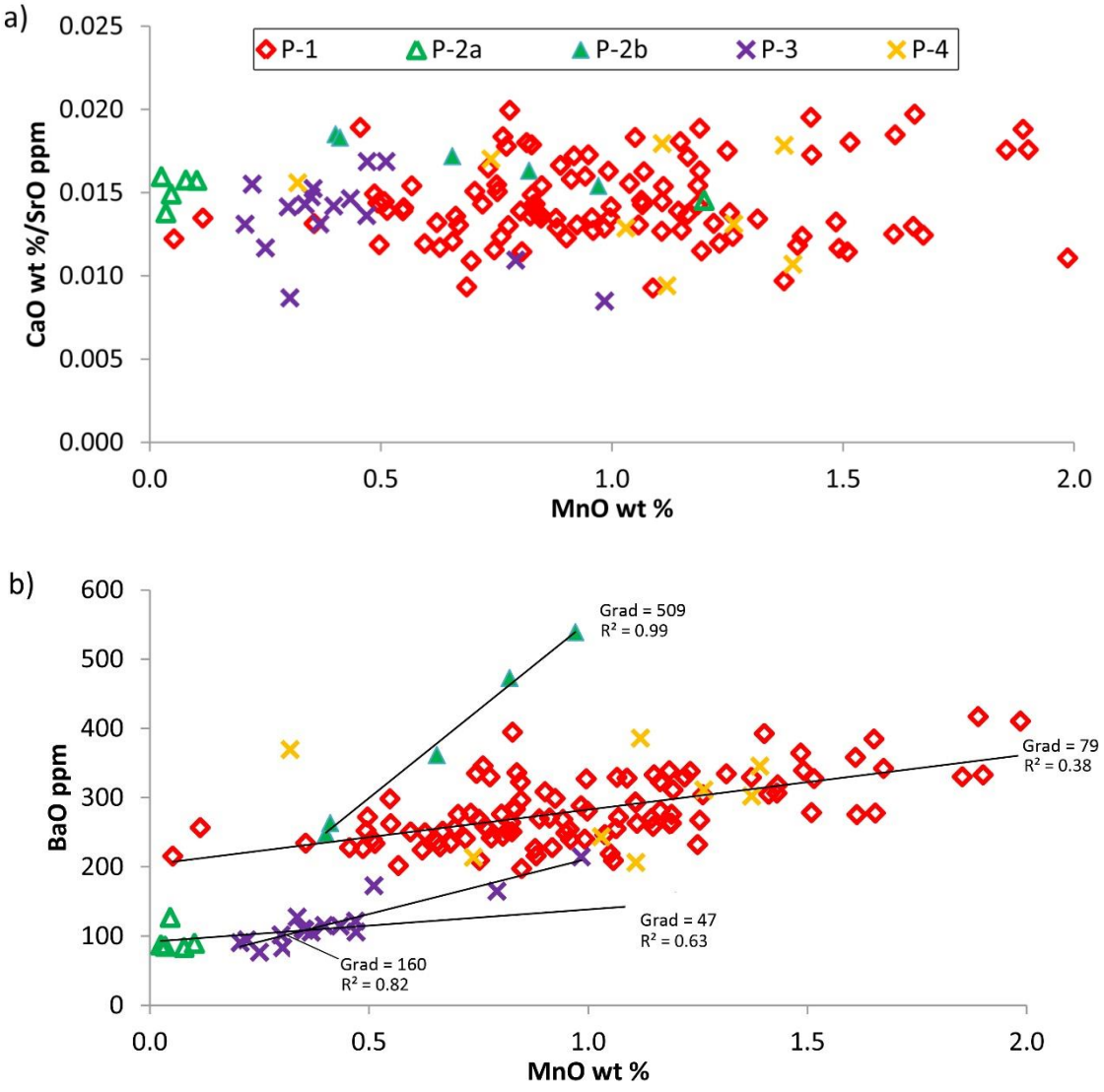


Figure 7.26 a) CaO/SrO vs. MnO and b) BaO vs. MnO for the plant ash glass groups. The latter image shows trend lines for selected groups with R^2 and line equations. Different line gradients (Grad) for BaO/MnO shown for each group suggesting separate manganese oxides sources. Grad is calculated from the line equations.

In Roman glass, manganese is associated with increases in strontium and barium (Brill 1988; Jackson 2005; Silvestri 2008). Figure 7.26a presents CaO/SrO versus MnO. As these elements strongly correlate, the SrO is normalised to the CaO content, and by plotting against MnO, the lack of resulting positive correlation signifies that there is no SrO component within the MnO source. Figure 7.27b presents MnO against BaO, and this time strong correlations are observed in P-2b (r^2=0.99) and P-3 (r^2=0.83), and a lesser correlation is seen in P-1 (r^2=0.39). No relationship is seen in the P-4 group and a trend line is not displayed. This not only demonstrates that BaO increases with MnO, but that each group has a slightly different BaO/MnO gradient, suggesting that a different MnO source was used for each of the compositional groups. BaO/MnO gradients, as read from the trend lines, are 79 for P-1, 508 for P-2b and 160 for P-3. This equates to manganese ores high in manganese oxide but with smaller impurities of barium oxide ranging from a ratio of 0.008:1 (BaO:MnO) in P-1 to 0.05:1 in P-2b. These barium quantities are not substantial enough to suggest the mineral psilomelane ($(Ba,H_2O)_2Mn_5O_{10}$) but imply a manganese oxide mineral of mainly pyrolusite (MnO_2) whilst containing smaller quantities of the hydrated mineral psilomelane.

Chapter 8

Results: Context and Chronology

8.1 Chronological Developments

This brief chapter will integrate the analytical findings of Chapters 6 and 7 with the contextual data of the samples: chronology, location and typology. This will explore general trends in compositional change through time. The samples are allocated into six chronological categories as detailed in Chapter 5. Individual sample information and descriptions can be found in Appendix C. Figures 8.1 presents the vessel frequency for each compositional group against their chronological category. Figure 8.2 presents diachronic change by illustrating vessel frequencies of the recycled and fresh glass vessels, as identified and defined in Chapters 6 and 7, for each chronological category and sorted into natron and plant ash glass types. The frequencies are given as percentages with the total numbers shown at the top of each column. Of the 292 analysed samples 279 are presented in Figure 8.1. (Thirteen samples are omitted: 5 due to strong colouration from lead or copper oxides and 6 for having missing or less precise dating.) Figure 8.2 presents 249 samples, with the P-4 and outlier samples omitted. It must be emphasised that there is probably an overlap and blurring between these chronological categories and therefore sample allocation between time periods may not be exact. Furthermore, it must be noted that absolute vessel amounts in each chronological category are influenced by sampling strategy and site context and do not reflect absolute quantities in each time period. However, the relative abundances of the different compositional types within and between time periods is likely to be representative.

8.1.1 Late Byzantine-Early Umayyad Period (7th century)

Vessels of this period principally derive from the Wilson's Arch and Secret Passageway excavations in the Old City, Jerusalem (A-5125). These were dated through style and context, although some vessels probably continue in date to the early 8th century. Sealed contexts from early Umayyad occupation layers at Sepphoris provided most of the remaining samples. Smaller numbers also came from Caesarea, Tiberias and Tel Rosh, with a single sample from Ramla (RAM 3592-01), a stemmed wine glass stylistically Byzantine but found in a later context. Vessels from this period consisted of a variety of types including oil lamps, wine glasses, bottles and bowls, some of which have applied trails, tonged, pinched or stamped decoration. They were mainly pale blue and greenish-blue in colour.

The 7th century vessels are almost entirely Apollonia-type glass (N-1), 44 vessels (98%). Egypt I type (N-4) accounted for a single object (TIB 5583-01), a greenish-blue bowl with pinched decoration. It is contemporary with Egyptian glass weights that share its composition (Gratuze and Barrandon 1990). The large quantities of Apollonia-type glass suggest that supply in Palestine at this time was dominated by local production from near the primary production furnaces identified at Apollonia (Tal et al. 2004; Freestone et al. 2008).

An estimated 31% of the samples are made of fresh glass (without traces of colourants which might indicate recycling) with the remaining 69% being recycled through either complete recycling or the addition of some cullet to fresh glass. This suggests that Apollonia-type production comprised the main pool of glass in use at workshops and that recycling with cullet was commonplace. The vast majority of fresh glass (all but one sample) came from the excavation at Wilson's Arch. These vessels (JER 5124-02-06; -08; -13-15; -21; -23; -29) originate from adjacent contexts – Loci 1512, 1515, 1516- and consist of bottles and oil lamps. In chapter Chapter 6 (Figure 6.8a) it was mentioned that these vessels shared a compositional similarity, however, this similarity is not close enough to suggest a single batch. Nonetheless, the large amount of fresh glass may potentially be linked with the redevelopment of this area near the

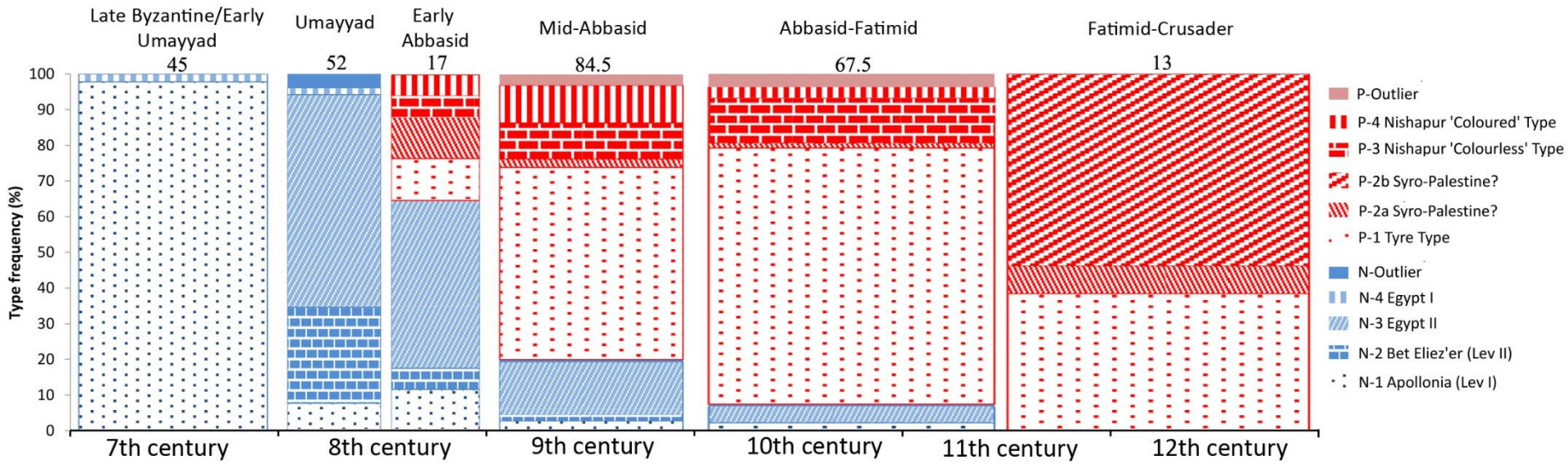


Figure 8.1. Frequency of compositional types (%) by dating category. X-axis presents time by centuries. Outliers are split into N-Outlier and P-Outlier for natron and plant ash respectively. Total counts for each column at top. N = 279.

Temple Mount, which was being rebuilt as a Muslim district at this time (Johns 2003, 426). With the exception of a single sample from Sepphoris, all the remaining glass have signs of recycling, suggesting that it was a standard practice of the 7th century.

8.1.2 Umayyad Period (early-mid 8th century)

The early 8th century saw diversification of the glass supply. The vessels from this period are Umayyad forms and have been identified as mainly from Ramla (founded c.715; 26 samples) dating from the earliest occupation layers of the city, and from Ahihud (13), dated by associated ceramics to the 8th century (Porat and Getzov 2010). Smaller amounts of material came from Jerusalem (5), Nahal Shoval (5), Tiberias (2) and Ha-Bonim (2). Note that in some cases a potential overlap with succeeding chronological categories is possible due to long-lived forms or poor stratigraphic resolution. The vessels of this period are mainly bowls, lamps and bottles. There are some more unusual types – distinctive horse shoe shaped objects (RAM 6490-02; 03) manufactured from Egypt II type (N-3) glass and a distinctive pilgrim flask (RAM-5947-22) made of an unknown natron outlier type. A range of decorative techniques are evident – mould blown, trailed, tonged, pinched, and a single wheel cut example (RAM 4768-01; N-3 type).

This period saw quantities of Apollonia-type (N-1) glass fall dramatically to 4 samples (8%) confined to contexts at Ahihud, Ramla and Tiberias. Fourteen samples (27%) of Bet Eli'ezer type (N-2) glass appear for the first time from five sites but mainly Ahihud, Jerusalem and Ramla, suggesting that production at Bet Eli'ezer commenced in the early 8th century, while the paucity of Apollonia-type glass suggests that production here had reduced or ceased. The higher silica/lower soda content of the Bet Eli'ezer glass type demonstrates a change in recipe, with a reduction in natron content, possibly denoting a shortage at this time (Freestone et al. 2000, 72). Most significantly for this period was a substantial influx of Egypt II type glass (N-3; 34 samples; 62%) making this the most frequent variety, and indicating a distinct shift in glass supply.

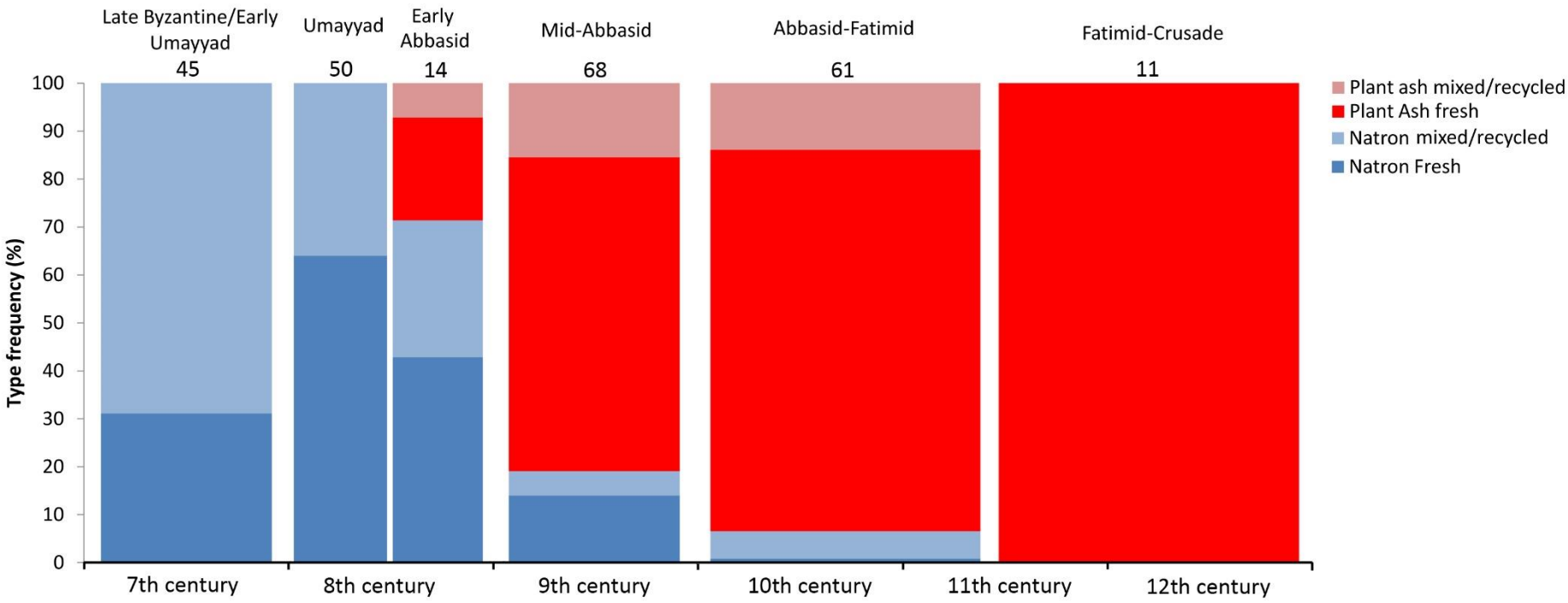


Figure 8.2. Frequency (%) through time of fresh and recycled glass sorted into natron and plant ash glass types. N = 249. Samples as Figure 8.1 but with the P-4 and outlier samples not included.

This glass is greenish-blue, and in most cases readily distinguishable from the pale 'aqua' blue of much of the N-2 glass. Egypt II (N-3) and Bet Eli'ezer (N-2) vessels are contemporary and found in the same contexts at some sites, e.g. L112 in Ramla (Permit A-5947); L16 and L30 in Ahihud and L1710 in Jerusalem (A-5124). This corresponds with the analytical results from an 8th century glass workshop at Tel Aviv that uncovered chunks of Bet Eli'ezer and Egypt II type glass at the same site (Freestone et al 2015). Such findings demonstrate that these types were contemporary and that a trade in Egypt II chunk glass was operating.

The number of vessels composed of fresh glass in this period increase to 64%. This is mainly due to increased quantities of fresh imported N-3 glass, particularly in the Ha-Nevi'im Nursery School assemblage from Ramla (Permit A-5947), and fresh glass of Bet Eli'ezer types. Evidently fresh glass of both types was entering into circulation at this time. In contrast, all but one of the N-1 type glass was recycled. Four samples of recycled glass dating to this time period was found along mixing lines between the main compositional groups as described in Section 6.6.2. Three vessels (AH 3758-05, -09, and RAM 5947-06) were recognised as mainly Egypt II glass but mixed with a significant portion of Levantine (N-1 or N-2) glass, thus implying that local Levantine cullet was being mixed into batches of Egypt II. More intriguing is the composition of RAM 5947-20, a vessel of an unknown type but from secure dating at the lowest level contexts (L114) at Ramla (A-5947; Haddad 2011). This glass was identified as a mix of N-3 Egypt II type and P-1 Tyre type (a plant ash glass) resulting in a glass with intermediate flux levels. This is possibly the earliest indication that any plant ash glass was in circulation within Palestine. It may suggest that plant ash glass was being used to extend natron glass, when production first took place.

8.1.3 Early Abbasid Period (mid-8th-9th)

In 750 CE the ruling dynasty changed from Umayyad to Abbasid. A small number of vessels could be dated to the mid-late 8th century, although overlap with the early 9th century is very likely. These were types dating to the beginning of the Abbasid

period or those of Umayyad-Abbasid typologies, e.g. RAM 4768-02; -03; (Gorin-Rosen 2010B, Figure 22.1 and 22.2) and RAM 5947-17 (Gorin-Rosen 2011, Figure 15.5). Most of the vessels of this date category came from Ramla (9), but there are further samples from Jerusalem (A-3835; 2), Ashdod-Yam (1), Ha-Bonim (2), Tiberias (2) and Tel Rosh (1). The general trend sees a continuing dominance of Egypt II (8 samples, 47%; N-3), demonstrating its importance at the expense of Levantine glass which is present in only 3 samples suggesting a possible downturn in glass production at Bet Eli'ezer, although the number of vessels present in this period may be too small to be fully representative.

Of particular importance are six examples of plant ash glass which make a first appearance at this time, and are the earliest so far recognised in Islamic Palestine. These plant ash vessels consist of three different production types. Two are of a Tyre type glass (P-1): an early Abbasid bottle (SEP 3791-13), although Gorin-Rosen (2010C) suggests that an earlier Umayyad date could be considered; and an early-mid Abbasid period bowl (JER 3835-06), which might date later. Two are of P-2a glass, a Syrian type, a mould blown vessel (RAM 4740-05) similar to 8th-9th century types from Fustat (Gorin-Rosen 2013, 171) and an early Abbasid bottle (HB 3032-04). The final two samples are identified as outliers but show similarities to Raqqa Type 4. One (RAM 5947-17) is a bowl popular during the 8th century but which was from a context shared with some Umayyad period vessels (Gorin-Rosen 2011) and the other (TR 6055-02) is a bottle dated to the 8th-9th century. Their dating is contemporary with late 8th/early 9th century production at Raqqa (Henderson 1995; 1999).

The appearance of plant ash glass at this early stage is an important finding. It gives the earliest indication of this glass type in Palestine and matches the dating from Raqqa (Henderson 1995; 1999). More significant is the finding of more than one compositional type suggesting that there were at least three production sites/regions making distinguishable compositions during the late 8th century.

The Egypt II type (N-3) glass was for the most part fresh glass and the Levantine (N-1 and N-2) types mostly contained recycled material. One plant ash glass possibly

contained recycled glass (Tyre Type, P-1; SEP 3791-13) and the others appeared to be of fresh glass.

8.1.4 Mid-Abbasid Period (9th century)

The 9th-10th century group was the largest with 84.5 analysed vessels. However, a number of samples, principally from Tiberias but also Ramla and Caesarea, could only be dated to the 9th-early 11th century and so covered two date categories. These samples were therefore divided and split evenly between the 9th-10th and the 10th-early 11th century groups. This allows the samples to be used, although chronological resolution is slightly reduced. Note that this gives rise to the "half" samples seen here and in Section 8.1.5. More details on dating is provided in Chapter 5. Of the 84.5 vessels, 22.5 vessels are shared with the 10th-early 11th dating category. The vessels present in the 9th-10th century date category (including the split vessels) come mainly from Ashdod-Yam (11.5), Caesarea (10), Ha-Bonim (12), Ramla (28) and Tiberias (9.5), with lesser quantities from other sites.

This period is the last in which natron glass is present in significant quantities. Seventeen natron glass samples are listed, representing 20% of the glass and identified from six sites. Most were of Egypt II (N-3; 13 samples; 15%), including a Co-blue scratch-decorated vessel (RAM 6297-06) and two manganese oxide de/coloured vessels (JER 5124-28 and NS 6362-08) also of this type. This possibly suggests a preference for the import of higher value coloured/decoloured vessels at this time. Levantine production is represented by just two samples of N-1 (JER 5124-29; -30) and one of N-2 (AY 2844-05). The form and fabric of the two vessels from Jerusalem have been dated to the 9th-10th century (Katsnelson forthcoming B), however, they appear in contexts with vessels associated to the early 8th century (L1516), and therefore might date earlier, although the N-2 sample appears to be a common Abbasid-Fatimid jug handle (Ouahnouna 2014, 67). These results suggest that there is no clear evidence that Palestine was still producing natron glass at this time and it is most likely that Levantine glass only persisted through recycling. The Egyptian (N-3) glass, on the other hand, is fresh and suggests that even though plant ash glass use was expanding, there

was continued production of natron glass in Egypt and export to Palestine, which suggests an ongoing demand for Egyptian glass in Palestine. The types associated with N-3 glass were mainly bottles, often with tonged and mould blown decoration, and one cobalt blue sample (RAM 6297-06) was scratch decorated.

The plant ash glass of this period is presented by five groups, discussed below in order of frequency. The largest is Tyre type glass (P-1) with 45.5 samples (54%). These were mainly found in Ramla and Ha-Bonim, although Tyre glass appears widespread. This glass is mainly colourless due to added manganese oxide, possibly added to combat the yellowing effect of the increased sulphur content of plant ash and stopping the formation of iron sulphide particles by creating more oxidising conditions within the melt (Brill 2009, 461). Types are mainly bottles, bowls, beakers – utilitarian forms – with the occasional decorated items using mould blown, tonged or trailed decoration. Some higher quality examples are conspicuous and might represent non-local vessels; these are discussed later. Glass of the P-4 group (9 vessels; 11%) are found mainly at Ramla, but there are single samples at Tiberias, Caesarea (W2S3) and Jerusalem (JER 3835-07). These are cobalt blue glasses, mainly as elongated bottles, identified as a Nishapur Coloured type of Mesopotamian origin. The next is P-3 (8.5 vessels; 6%), a Nishapur Colourless type also of Mesopotamian origin possibly produced near Samarra. These are colourless vessels, tending to have high quality fabrics with wheel cut or mould blown decoration. These on the whole come from Ramla, but with single examples from Sepphoris and Ha-Bonim. The final group recognised is two P-2a Syrian types with an unknown production location but most probable of Syrian origin. Unlike the other groups, this glass is not seen in Ramla. Two final vessels are unassigned plant ash outliers, JER 3835-07 and CEA 6194-01.

The proportion of plant ash glass providing evidence for recycling is much lower than is typical for natron glass. This could result from inaccurate recognition as plant ash glass (discussed in Section 7.4) as it naturally contains much background levels of colourant elements than natron glass as colourants are imparted by the plant ash and also by the sand. This difference is clearly seen by comparing the colourant element levels of the glass chunks and waste from Bet Eli'ezer and Apollonia (Appendix A), of which CuO,

PbO and CoO are generally <10pmm, against those from Tyre (Appendix B), which have levels around a magnitude higher. However, the plant ash glass from Banias does not exhibit such high levels, with CuO present in a range of 11-20ppm, it might suggest that the content in the glass from Tyre was not typical. Alternatively, it does seem probable that a substantial quantity of fresh glass was entering circulation as natron glass was being superseded at this time. It might be that total quantities of glass in circulation increased during this time. The recycled plant ash glass itself is recognised almost universally as Tyre type suggesting, along with its greater abundance, that this was the principal glass in circulation. P-3 and P-4 did not exhibit recycled examples.

8.1.5 Abbasid-Fatimid Period (10th – mid-11th century)

This period has 67.5 vessels (including 22.5 vessels split with the 9th-10th century). Natron glass is represented by only three vessels (one N-1 type, two N-3 types), all manifesting signs of recycling, suggesting that Egypt II (N-3) glass was no longer being imported and that production may have ceased, most likely during the preceding century. Plant ash glass continues to grow in dominance, with P-1 (Tyre type; 48.5, 72%) the most frequent, followed by P-3 (8.5, 13%), P-4 (2; 3%) and the P-2a (1) and a further two samples of plant ash glass outliers. The Tyre type glass tends to be a mix of utilitarian types (bottles, bowls, jars), found at most sites, but the occasional superior quality objects with wheel cut, or relief cut decoration is present. Tyre type glass also contains almost all the examples of vessels with parallels on the Serçe Limanı shipwreck (c. 1025 CE). The two plant ash outliers (JER 3835-10 and RAM 4740-11) were identified as a mix of Egypt II types and Tyre glass, indicating that the remaining natron glass cullet was being combined with the dominant plant ash glass. As before, there is a significant percentage of fresh plant ash glass and any recycled glass is Tyre type only.

8.1.6 Fatimid-Crusader Period (mid-11th – 13th century)

This final date category spans the mid-11th to 13th centuries. It contains fewer samples than the previous groups and it is at the boundary of the period in question for this thesis. Tyre type is present but a new compositional group, P-2b, is most frequent. This is an unknown Syrian type unique to this period and only found at Bet Shean. It is an unusual group as it does not contain manganese oxide, and is mainly colourless but with pale blue and amber examples and a range of vessel forms. It suggests a localised type with a later production date, although, whether it had a wider distribution cannot be deduced due to the limited sample selection in this time period. Other sites (Ramla and Ha-Bonim) continued to use Tyre type glass. None of these glasses show indications of recycling (although P-2b does have particularly high contents of colourant elements) and no natron glass appears from this time period.

8.1.7 Summary of the Chronology Trends

This section has highlighted a number of major trends in the chronological development of the identified compositional types. In the early 8th century an abrupt change in the location and recipe of Levantine production occurred, accompanied by an influx of imported Egyptian glass. The late 8th century is characterised by a decline in Bet Eli'ezer production and the initial appearances of plant ash glass. These developments taken together indicate a dramatic shift and subsequent reduction in Levantine production during the 8th century. The results also date the decline in the importation of Egyptian glass to the mid-late 9th century, suggesting that production in Egypt continued for up to 100 years after Levantine natron glass production ceased. In addition, this section charts the rise to dominance of plant ash glass from Tyre starting in the 9th century and the emergence of new glass types from Mesopotamia and Syria.

Chapter 9

Discussion

9.1 Introduction

The analytical results identified several natron and plant ash glass types, while Chapter 8 integrated these data with the sample contextual information to establish the major diachronic developments in glass production and supply during the Early Islamic period. The present chapter will provide a more detailed examination of these developments within their wider historical, archaeological and economic contexts in order to ascertain how the glass industry adapted in the period after the Arab conquest. The main aims of this thesis will be discussed in four parts: i) an investigation of how the natron glass industry in Palestine developed; ii) discussion of the reasons for the adoption of plant ash technology and the natron glass production; iii) examining the potential origins of plant ash glass technology; and iv) investigation of the organisation of production and supply of plant ash glass in Palestine and how it changed through time.

9.2 Levantine Glass in the 8th Century: Decline in Production and Shifts in Supply

The Levantine glass industry experienced a number of critical changes in the 8th century. At the core of this discussion is the premise that Palestinian production was under strain and underwent a period of contraction starting from the beginning of this century. It will be argued that the adoption of a new soda-reduced glass recipe and the loss of dominance of Levantine glass to non-local types were linked to the increasing unavailability of natron within Palestine, eventually leading to the cessation of

production in Palestine and the adoption of alternative technologies – namely plant ash glass.

9.2.1 Production at Apollonia

Apollonia-type glass (Levantine I) was the predominant type in the Late Byzantine period (5th-7th century) Palestine and is recognised from numerous Byzantine sites within Palestine, such as pre-Islamic south Ramla (Tal et al 2008), Dor (Freestone et al 2000) and a secondary working site at Apollonia (Freestone et al 2008A), and also outside of Palestine, for example Cyprus (Freestone et al 2002A; Ceglia et al 2015); Jordan (Schibille et al 2008; Rehren et al 2010; Abd-Allah 2010; al-Bashaireh et al 2016); and Italy (Silvestri et al 2005; 2008; Verità 1995, among others). The results here demonstrate that there appears to be no interruption in the production of an Apollonia-type glass, or change in recipe or technology, until approximately 50 or so years after the conquest in 640 CE, around the late 7th/early 8th century. This finding is generally consistent with what is known of the conquest, in that it had little immediate effect on the everyday lives of the population of Palestine (Milwright 2010A, 44), or on the material culture (Schick 1998, 94; Walmsley 2007, 53; Carboni 2001, 15; Brosh 2003, 319), showing that despite the major political changes, everyday activities remained largely the same.

Production of Apollonia-type glass is currently identified to four furnaces found at Apollonia (Gorin-Rosen 2000; Tal et al 2004), although other furnaces are identified to the nearby area. They have been dated using small quantities of associated finds, or from nearby debris fills, to the 6th-7th century, Late Byzantine period (Freestone et al 2000, 67; Freestone et al 2008A, 68 and 70). The dating of the N-1 group samples extends beyond this and suggests that additional furnaces at Apollonia, or in the close nearby area, operated to a later date. Given the large quantities of glass of this type in Palestine and abroad it is most probable that a number of furnaces were in operation during the Late Byzantine period which may have started to reduce in number in the Islamic period. The lack of a large-scale production site, like that seen at Bet Eli'ezer, may be due to furnaces relocating to new fuel sources every season or so, however, it

might also indicate a smaller scale of production, such as family or privately run production units. The high percentage of recycled glass identified during the 7th century, the highest for any time period, may suggest that the output of the Apollonia-type glass was not necessarily that large at this time and that recycling of cullet into batches of fresh glass, was commonplace and an important aspect of glass working.

9.2.2 Production at Bet Eli'ezer

The results have indicated that in the early 8th century quantities of Apollonia-type glass in Palestine reduced sharply and a new type with close compositional similarity to Bet Eli'ezer appeared. The principal identifying change was in recipe, with a shift in soda content downwards and a rise in silica. The original dating for the primary production site at Bet Eli'ezer was suggested as the 6-7th century based on a few associated finds (Freestone et al 2000, 67) but this dating was never secure due to the paucity of datable material and the slow advancement of material culture in that period. Compositional similarities to glass analysed from 8th century Ramla revised this date later (Freestone et al 2000, 72). The results presented here agrees with this later date, with the fresh glass of a Bet Eli'ezer type appearing in the 8th century and lasting until the late 8th, suggesting a production span of this type of approximately 50 to 100 years.

The site of Bet Eli'ezer is about 8 km inland and farther north than Apollonia. It would have still been possible to procure beach sand for use, although it is also possible that a *kurkar* (fossil beach sand) source was exploited. Production appears to have been on a large scale and well organised, with 17 tank furnaces identified (Gorin-Rosen 1995; 2000). Some furnaces were scattered; others were arranged side by side. This site probably represents a number of seasons activity, although excavations indicated the site to have one stratum, suggesting production over a short time period (Gorin-Rosen 2000, 52). Evidence of additional glass debris in the local area indicates that these furnaces were situated within a larger zone of glass production, although these sites have not been excavated (Gorin-Rosen 2000, 54). This suggests a regional operation whose production possibly continued over a longer period than that evidenced from

Bet Eli'ezer alone but most likely using the same recipes and raw materials. Thus, glass was produced in this region over 50-100 years using a similar recipe, rather than at the Bet Eli'ezer site itself. Based on the available data it is difficult to reach conclusions on the scales of production at Bet Eli'ezer versus Apollonia. Eli'ezer had 17 furnaces, multiple campaigns of production likely operated during the summer months each year. This contrasts with the four known tank furnaces at Apollonia, however, the surrounding region likely accommodated many more not yet excavated. The larger scale and potentially more intensive production at Bet Eli'ezer might signify a difference in organisation, such as a change from a collection of private enterprises at Apollonia to a possibly state organised operation. There is precedent for this in the metal smelting industry in Syria and Palestine, of which smelting sites display evidence for state organisation during the Umayyad and Early Abbasid period through the use of standardised structures (Walmsley 2000, 309-10). Increased requirements for glass in state building projects, for example, may have produced a necessity for state controlled production. On the other hand, it might reflect the environment, Bet Eli'ezer was wooded with plentiful rainfall (Gorin-Rosen 2000, 53), meaning more glassmaking campaigns could be run before the fuel of that area was exhausted. Apollonia was a coastal site that cannot support woodland (Tal et al 2004, 61). Production may have had to be less intensive and/or more dispersed in order to better utilise a more limited supply of fuel.

The timing of the change in production site coincides with the influential reforming reigns of Caliph al-Malik (r. 685-705) and al-Walid (r. 705-15). As discussed in Chapter 2, Al-Malik was instrumental in reforming the administration of the newly created Islamic state (Hawting 1986, 61-68; Donner 1986, 293). He increased centralisation, made Arabic the official language of bureaucracy (Robinson 2010, 218-9), implemented the first Islamic coinage, and a new system of weights and measurements (Schick 1998, 95-6; Walmsley 2007, 59-64). All of these developments were to have a beneficial effect on the late 7th and 8th century economy of Syria and Palestine (Walmsley 2000; Wickham 2004). It was also a period of state construction, with the completion of The Dome of the Rock in 692 (Johns 2003, 416), the first large-scale Islamic monument. Monumental construction continued under subsequent

caliphs with the Aqsa and Damascus Mosques under al-Walid, and market and shop construction initiated by Caliph Hisham (r. 724-743), for example, a new commercial street at Bet Shean (Tsafrir 2009). The Mosques and Palaces were often decorated with mosaics after the Byzantine practice (Henderson 2013, 255 and references within), and further required lamps, windows and vessels, which would have added to the demand for glass. There was also a strongly growing economy, driven by a wealthy Muslim elite, large populous towns and state patronage within cities such as Ramla and Jerusalem. This drove craft production, which was further supported by pro-commerce policies, such as new trade infrastructure (e.g. roads, caravanserai) and new regulations (Walmsley 2000). It is therefore likely that demand for glass for construction and local consumption was high at this time during the 8th century, potentially fuelling demand.

A number of potential factors can be suggested as to why production around Apollonia was abandoned in favour of Bet Eli'ezer. The conquest cut Palestine off from Mediterranean trade with Southern Europe and the Byzantine Empire, shifting the focus of trade inland within Palestine and Syria, and eastwards towards Jordan and the old Sasanian territories of Mesopotamia (Morony 2004). The 7th century also saw periodic raiding by the Byzantine navy (Avni 2014, 321), culminating in the occupation of Caesarea between 685 and 695 (Petersen 2005B, 86). Post-conquest instability around the coasts resulted in a general depopulation of this region. This only began to improve in the late 7th-early 8th century with the building of coastal fortresses (Raphael 2014). The lack of security combined with the loss of contact with Mediterranean markets may have removed some of the benefits of Apollonia as a glass-making site, encouraging a more inland location well-connected to the road network. Fuel may also have been a deciding factor, especially when combined with reductions in the natron content of the glass that followed. The lower natron content would have caused the melting temperature of the glass to increase, requiring more fuel. Therefore, a combination of factors may have acted together to favour production at Bet Eli'ezer.

The glass from Bet Eli'ezer does not appear to be as ubiquitous as that of Apollonia-type. For instance, in the samples recorded here, at no time is it the dominant type in Palestine, despite being the only locally produced type in the 8th century, although, the

recycling of Bet Eli'ezer glass with existing Apollonia-type cullet may hide some of this glass type. Nevertheless, it is clear from the examples of 'fresh' Bet Eli'ezer glass that this glass type was entering into the regional glass supply, but there is little evidence that this type was exported from Syro-Palestine. As yet, there are no examples from Mediterranean contexts, although this can be easily explained by the collapse of Mediterranean trade routes as evidenced from the quantities of shipwrecks and changes to pottery distributions (Kingsley 2009, 35; McCormick 2012). Four samples are recognised from Umm el-Jimal, Jordan (al-Bashaireh et al 2016). Further samples are described from 8th century Raya (Kato et al. 2009; Shindo 2007, 100), however, while Bet Eli'ezer (Levantine II) type is reported, the absence of analysis for soda and silica, key diagnostic oxides in the differentiation of Bet Eli'ezer and Apollonia glass types, mean the identification of Bet Eli'ezer glass cannot be confirmed. The average lime content (8.28%; *ibid,* 1703) is more consistent with an Apollonia-type glass despite the late date, alternatively suggesting that this is a late shipment of glass produced in the region of Apollonia. Moreover, this composition matches that of the Levantine glass from Raqqa (Raqqa Type 3; Henderson et al 2004), which also does not display a Bet Eli'ezer production signature. Therefore, the vessels from Raya and Raqqa potentially suggest an alternate production location, not related to Bet Elie'zer production, and this is discussed more below. Therefore, while some of the absence of Bet Eliezer glass may be due to a lack of analyses of glass of suitable date, on the whole the evidence suggests that Bet Eli'ezer glass may have had a more localised distribution than other types and was not exported.

Investigations of ceramic vessel distributions of locally made pottery in Palestine during the 8th century shows a similar pattern of localised distribution (see Walmsley 2012; Holmqvist and Martinón-Torres 2011), with Walmsley suggesting a 50-100km trade in vessels around ceramic production centres. It should be noted, however, that the organisation of the glass and ceramic industries were different as glass was traded as raw chunks and less so as vessels, but nevertheless, Walmsley (2000) explains that the localised nature of 8th century trade in Syro-Palestine may have been due to the greater independence of the different provinces at this time and the lack of large scale wealth redistribution seen during the Roman and Byzantine periods. This trend

towards more localised distributions of products may have influenced the movement of raw glass at the time. The model of trade active in this period appears to have been based on overlapping regional trade networks, such networks for Syria and Palestine have been mapped from known trade fayres and main roads (Bingelli 2012). This may have reduced the quantities of glass being exported between regions, however, as is shown below, Egyptian glass was being traded inter-regionally, even if Levantine glass was not.

An alternative explanation for the local distribution is that production at Bet Eli'ezer was either in insufficient quantities for local demand (either due to high local demand or a lack of production) or that it was not a popular glass type and that other types from Egypt were preferred, either due to the inferior quality or poor workability of the glass from the Bet Eli'ezer, or due to it being more expensive. The modification in recipe meant this glass type was harder to work, while increased fuel usage and a probable increase in the cost of the natron itself might have made more expensive to produce. These reasons might explain why the glass was not widely exported, and it is certainly true that Bet Eli'ezer glass was not able to dominate local and foreign markets as Apollonia production had done. The appearance of large quantities of Egyptian glass in the early 8th century and plant ash glass in the late 8th century is further evidence, and possibly suggestive of a decline in Levantine glass production.

9.2.3 Change in Recipe

As noted, production at Bet Eli'ezer is characterised by a recipe containing low quantities of soda, up to 20% less than the preceding Apollonia-type glass. This has been suggested to indicate falling natron supply in Palestine (Freestone et al. 2000) either as a result of decreased availability or increased cost which caused glassmakers to reduce the content within glass. There are a number of possible explanations for a decline in natron availability within Palestine. A breakdown in Eastern Mediterranean trade is a possibility, and while this might be true for Byzantine and European territories, trade from Egypt appears unaffected as evidenced from Egyptian imported glass and numerous Egyptian pottery finds in Palestine during the Umayyad and Early

Abbasid period (see Taxel and Fantalkin 2011). Moreover, the existence of vessels with reduced soda recipes continues for a relatively long period, possibly around 50-100 years, and this implies long-term causes with more permanent change, and not a period of trade disruption. These changes do not seem to impact the Egyptian industry during the 8th century, presumably due to its closer proximity to the natron source and easier access. Nonetheless, the duration suggests that problems in the natron supply most likely originated at the source.

9.2.4 Appearance of Egyptian Glass

Egypt II was important in the supply of glass within Palestine, establishing itself as the most abundant type recognised in the 8th century. Due to inherent transport costs, locally made glass would normally be expected to be cheaper and more readily available. Therefore, the extensive use of Egyptian glass in Palestine suggests that a change in the Levantine industry was occurring, possibly a contraction of production due to natron shortages, or increasing cost of local glass again due to a lack of natron combined with increased fuel costs, or due to increased local demand for more glass. A further factor may be the superior working properties of Egyptian glass, glass workers may have preferred its larger working range and lower working temperature (Freestone et al. 2015). Egyptian glass was a different colour (greener) and there might also have been a changing aesthetic preference against the pale blue of typical Bet Eli'ezer type glasses, although with tastes tending towards colourless fabrics in the Abbasid period, this seems less likely. Egypt II glass was traded and worked from chunks as evidenced from analyses of 8th century workshop waste and chunks from Tel Aviv (Freestone et al 2015). Large quantities of Egyptian pottery also appear during this period, evidenced from sites such as Jerash in Jordan (Morony 1995, 18), Sepphoris, Ramla, Caesarea (see references within Taxel and Fantalkin 2011), and therefore glass may have formed part of a wider economic expansion of Egypt at this time.

9.2.5 Appearance of Plant Ash Glass

In the late 8th century three plant ash glass types are identified, suggesting that at least three production sites were operating at this time. One sort was Tyre-type

glass which predates the 10th-11th century production so far identified at Tyre (Aldsworth et al 2002; Jennings et al 2001), implying that production around Tyre commenced earlier. The possible Raqqa Type 4 samples identified here are contemporary with production at Raqqa (Henderson 1999; Henderson et al 2004), although this designation was not certain. Finally, there were two samples of unknown Syrian type. The appearance of plant ash glass alongside imported Egyptian glass is further evidence that Levantine production was unable to satisfy demand in Palestine. The Syro-Palestine economy was largely market driven (Walmsley 2000; Haldon 2012) and a combination of inferior working qualities of the glass, potentially increased cost of the natron, and also potentially increased demand for glass, may have been important determining factors in the adoption of plant ash glass. A vacuum in the market in the late 8th century allowed plant ash glass to establish itself and become dominant probably as a result of the decline in the Levantine natron glass industry.

There are some distinct advantages to plant ash glass, plants suitable for the production of alkaline ashes were ubiquitous in the Near East (Ashtor 1992) making flux more accessible for local and regional production, and eschewing the necessity for long trade routes. Being readily available and therefore most likely cheaper, plant ash glass could have higher flux contents, meaning that melting temperature could be lower, making glass less expensive to produce and easier to work. The adoption of plant ash glass may have stemmed from the requirement for economic alternatives to imported natron and Egyptian glass and was consequently driven by market forces.

The discussion so far has created a picture of a contracting industry in Palestine, unable to meet local demand. However, as mentioned above, large quantities of Levantine glass have been identified at Raqqa, Syria dating to the late 8th-early 9th century (Henderson et al. 2004), and this is unaccounted for. This dates to around the period in which Bet Eli'ezer was in operation, and while the glass has been confirmed to be Levantine by isotopic analysis (Henderson et al. 2005, 670), it does not conform compositionally to Bet Eli'ezer production, nor does it precisely match Apollonia-type glass. The glass from Raqqa has levels of soda higher than Bet Eli'ezer although less than Apollonia-type glass and also higher lime than Bet Eli'ezer production (see differences in Chapter 3, Figure 3.7). The Raqqa glass contradicts the proposed

narrative of a natron shortage in the Levant. Assuming that the analyses are compatible, it potentially suggests that an alternate production site less affected by a lack of natron was operating in the late 8th century. One potential site is Beirut, which is known to have been producing a 'Levantine' glass during the Roman period (Henderson 2013, 215-222). Tyre is another potential option, documentary evidence reported that glass workers were transferred here from Palestine during the early 8th century during the rule of Caliph Hisham (Engle 1973, 7) and therefore a nascent natron glass industry not yet recognised might have been operating (more details in Section 9.4.2). However, production at sites such as Beirut or Tyre would also have been affected by the natron shortages. Much of the glass at Raqqa was used within Palaces built for Harun al-Rashid (Henderson 1999), possibly suggesting that production may have been state organised, therefore an alternative explanation might be that the Levantine glass consisted of a specifically ordered consignment of glass and was a-typical of glass in general circulation. Alternatively, it could be that the glass was recycled cullet and Apollonia and Bet Eli'ezer types were mixed, this would explain the slightly reduced soda content, although the lime content would still be too high.

9.3 Transition from Natron to Plant Ash Technologies

9.3.1 Chronology

While problems of natron availability are apparent in early 8th century Palestine, in Egypt these problems do not seem to have been felt until the 9th century with the recorded appearance of plant ash glass. By the 10th century Egypt II glass in Palestine is reduced to only a few recycled samples, suggesting production had ceased in Egypt in the mid-late 9th century. This turn of events is supported by evidence from Egypt, which dates the final Egypt II glass weight to 868-893 CE (Gratuze and Barrandon 1990), suggesting an end of production in the late 9th century. Data from Sayre and Smith (1961) indicate a similar although slightly earlier 833-842 CE date for their last natron glass weight. These dates correlate with the last Egypt II glass found at Raya

(Kato et al 2009, 1705) and at Tebtynis (Foy et al 2003B), also dating no later than the 9th century.

Why did natron glass production discontinue in Egypt? As already discussed for Palestine, a longer-term issue with the supply at the natron source, and/or the distribution of natron within Egypt seems the most probable answer. These issues appear to worsen, not only affecting Palestine but spreading to Egypt in the mid-9th century. This section will attempt to identify causes that may have acted together to disrupt natron production and supply and which might explain the changes in glass production observed here. A background to the history of natron extraction will be provided, followed by a discussion of the short and long-term factors affecting the use of natron in the glass industry.

9.3.2 Background to Natron Extraction

Natron as a raw material was briefly discussed in Chapters 3 and 5. As yet, the only deposits recognised to have been used in glass production in Antiquity are those from Egypt as evidenced by boron isotopes investigations (Devulder et al 2014) and documentary sources (Freestone 2008). Both Pliny (*Natural History* 31.46; translation in Bostock and Riley 1893) and Strabo (*Geographica* 17.1.22-23; translation in Jones 1917-32, 73-75) describe the location of *'nitre'* deposits near Naucratis, north of Memphis, which has been identified as the lakes of the Wadi Natrun (see references in Shortland et al 2006A). Other natron sources are mentioned by Pliny, such as those in Lydia, Thrace and Macedonia. Some sites have also been investigated chemically, such as those in Greece (Ignatiadou et al 2005; Doksika et al 2009) and Libya (Devulder et al 2014), however there is no evidence of their use in glass production. Further discussion is presented in Shortland et al (2006A, 523-4). In later Byzantine periods, an Anatolian source has been evidenced by compositional analysis and was used in the production of a high boron glass type (Schibille 2011; Rehren et al 2015).

Within Egypt, the principal natron source is the Wadi Natrun, although extraction from other lakes at al-Barnuj in the Western Delta and al-Tarabiya in the Eastern Delta have also been proposed (Shortland et al 2006A; Décobert 2003). The Wadi Natrun is a

series of evaporitic lakes in a depression around 100 km north-west of Cairo, situated along the road linking Cairo to Alexandria. The lakes stretch around 50 km in length and are 10 km wide (Shortland 2004B, 497). The number of lakes can vary seasonally and yearly depending on water level, tending to merge in the winter and fragment in summer. In modern times, around eight permanent lakes are noted (Shortland 2004B). They are an open system, filling through ground water during the winter months, whereupon the incoming water percolates through the surrounding soil dissolving out salts (Shortland 2004B, 502). Levels start to reduce from April (Lucas 1912, 14) and continue to decline during the summer months via evaporation, leading to the formation of evaporitic crusts at the surface and the edges of the lake, which are collected (Shortland 2004B; 2011). A number of studies have analysed the lakes and have found that mineral contents vary between lakes, but also between years (see Chapter 5).

Some of the best descriptions of extraction come from Andréossi (1809; Nenna 2015, 15) who describes the removing of minerals in blocks 60lb in size using iron tongs. He remarks on the mechanical separation of the natron (trona) from the salt (halite) layers (Andréossi 1809, 284), which were then discarded. Pliny describes natron piled up in heaps at the side of the lake, commenting that they survived a considerably time before dissolving. Modern day extraction still describes natron piled as blocks in heaps (Shortland 2004B). Pliny further explains how the natron was put into dried, pitch sealed, vessels with the pitch used to prevent 'melting', most likely referring to the dissolving of trona in water. It could be that the highest grades, which Pliny reported as *'very fine… extremely spongy and porous'* (*Nat Hist* 31.48 in Bostock and Riley 1893), were transported this way. Taxel and Fantalkin (2011) also comment on the possible transport of natron in red-brown ovoid amphorae made at the Wadi Natrun during the Islamic period (ibid, 82) as first suggested in Ballet and Dixneuf (2004). This seems unlikely for glassmaking due to the large quantities of natron involved and the associated additional costs of the ceramic and the extra weight, although such a process would effectively protect the natron from the elements during transportation, particularly for a sea voyage.

The closest town to the Wadi Natrun was Terraneh/Terenouthis, a 12 hour walk (Wilkinson 1843). It was also a river port on the Nile, and allowed the shipping of natron to the ports in the Delta. This was where the workers lived and where the natron was processed in more recent times. Writing in the early 19th century, Andréossi states that of the six lakes, labourers from Terraneh exploited one and nomadic shepherds exploited another, indicating that not all lakes were used, or could be used, during a single season. The natron was extracted by hand and it is noted that once the mineral was removed down to soil level the area had to be left to recuperate for between four and six years before further extraction could take place (Berthollet 1800). Therefore, sufficient thicknesses of natron might take years to replenished. Andréossi (1809) describes how the natron was transported by a caravan of 150 camels and 500-600 donkeys (Nenna 2015). A theoretical load of around 431 tonnes for one caravan is posited by Sapsford (2009, 233), which implies 3 to 4 caravans a year as suggested by annual extraction accounts (see below). There are 19th century reports that natron was processed at Terraneh by dissolving in water and then oven drying (Wilkinson 1847, 240). Engle (1988) also comments that natron, in ancient times, was *'fritted'* into a rectangular mass before transport, although the nature of the fritting process remains unexplained. Some archaeological evidence is provided (Engle 1988, 67), however, this appears to be more likely a stage in glass making at a nearby glass furnace.

The processes of natron extraction appear to be labour intensive but not requiring any large-scale infrastructure. Workers lived at Terraneh and most likely stayed at the Wadi Natrun during the extraction period. Employment was seasonal, and the use of caravans in the 19th century suggest large quantities of natron were transported en masse, although in earlier periods transport might have been more regular. Terraneh was situated on the Nile, which would provide easy access to the ports on the Delta for export to Palestine and elsewhere.

Natron represented a considerable source of revenue and has in various times been controlled by the state. Lane-Poole (1901, 303) reports that during the Ptolemaic period it was a state monopoly. In the 4th century, papyrus P. Abinn 9 reports that natron extraction was a monopoly controlled from Terraneh. During the Tulunid period

(mid-8th century) and continuing into the Fatimid era documentary sources suggest it was once again made a state monopoly (Lane-Poole 1901, 43; discussed further below).

9.3.3 Short Term Factors Affecting Natron Extraction and Trade

As has been related, evidence suggests that natron use in Egyptian glass ended in the mid-late 9th century (Sayre and Smith 1971; Gratuze and Barrandon 1990). Over the years numerous papers have discussed the change (Shortland et al 2006A; Whitehouse 2002; Saguì 2007; Picon et al 2008; Nenna and Foy 2001; Henderson 2013) providing various long and short-term reasons that might account for why natron may have been restricted for glass working.

Shortland et al (2006A) and Whitehouse (2002) have highlighted political instability within Egypt during the 9th century as a principal cause for the discontinuation of natron glass production caused by disruption to extraction and trade. There are a number of accounts detailing disruption in the West Delta and Wadi Natrun during the Early Islamic period. Shortland et al (2006A) suggests instability started in the mid-8th century with the abandonment of Naucratis – the main river port on the delta between Terraneh and the sea (Shortland et al 2006A, 527) – although the evidence for abandonment is inconclusive with evidence for later habitation in the surrounding areas (Coulson 1998, 14). Nevertheless, this potential disruption would have been too late to account for the changes in natron use in Palestinian glass.

In the 9th century insecurity in Egypt and Palestine became widespread due to the civil war following Harun al-Rashid's death. It lasted from 809 to 832 and caused much disturbance and damage in the Western Delta (Whitehouse 2002, 194), although Shortland (Shortland et al 2006A, 527) notes that the Wadi Natrun underwent *'restoration'* after 832. Berber raids in 809, 817, 867/8 and 871 are recorded in the destruction of churches in the Delta (ibid), while Whitehouse puts particular emphasis on a rebellion in Alexandria, in which Andalusi exiles occupied the city between 815 and 826. As Alexandria was the main port of Egypt and most likely one of the principal ports for the shipping of natron, Whitehouse (2002, 194) conjectures that trade

disruption of natron to Palestine was highly probable, however the timeline of Levantine production presented here suggests that natron glass production had already stopped by this time. In the mid-late 9th century, the period in which the last natron glass dates, rebellions in 862 led to damage of the monasteries around the Wadi Natrun, with the worse destruction reported in 867/8 and 871 (Shortland et a 2006A, 528). Shortland advocates that extraction sites in the Wadi Natrun were probably badly damaged by the rebellions, although no archaeological evidence is presented.

The problem with the proposal that political instability caused the cessation of natron extraction and trade, is that it fails to explain why natron use did not resume once stability was restored. Natron extraction does not require large scale infrastructure which might require time or money to replace, and so should have been relatively easy to resume. Natron extraction is documented from the 12th century (Décobert 2003, 126), demonstrating that extraction did continue, however it does not appear to have been used in the making of glass. The timing of the suggested instability also does not explain why natron shortages occurred in Palestine during the 8th century, before the events listed. There is also the matter of other periods of destabilisation which did not result in the stoppage of natron glass production, for example, the Persian occupation of Egypt from 617-629. This period saw much disruption, with Kaegi (1998, 43) suggesting a decline in infrastructure within Egypt, the stoppage of coastal trading and a weakening of the economy, although he notes that the invasion was not particularly destructive (ibid, 42). A Byzantine rebellion in 608-610 between Heraclius and Phokas reportedly caused much more damage, disruption and numerous deaths within Egypt (Kaegi 1998, 37). However, neither of these events, nor the Arabic conquest itself, appears to have had a noticeable impact on natron glass production. Therefore, political instability alone seems an insufficient explanation for the discontinuation of natron glass making in Egypt and appears unrelated to the end of Palestinian production.

Such disturbances, however, might have formed one factor in a series of changing conditions that would have made natron use in glass making no longer viable, such as changing administrative arrangements, new taxes or increased costs. Around 861, al-

Mudabbir (the finance minister under Yezid, the governor of Egypt) imposed new tariffs on goods which included '*caustic soda*', probably referring to natron (Bianquis 1998, 92). The taxation of natron continued until the 15th century (Rabie 1972, 85). Then in 864/865 al-Mudabbir made natron extraction a government monopoly (Lane-Poole 1901, 43; Rabie 1972, 85). Natron supply up till this point had been unrestricted. It was just after this time, during the period of Tulunid rule, that new natron sources began to be worked for the first time, such as that at Lake Tarabiya, as recorded by al-Qalqashandi (1355/56-1418) in his encyclopaedic book *Kitab Subh al-a'shá* (Lane-Poole 1901, 304). Although Décobert (2003) disputes the designation of Lake Tarabiya and suggests it could be an alternative site, it nonetheless appears that during the 9th century there was an attempt to control production and maximise profits for the state by opening up new extraction sites. Ibn Mammâtî (1169-1209) recorded an account of the Egyptian government in his book Kitâb *Qawanin al-Dawawin* (Statutes of the Councils of State) written during the reign of the Ayyubid Sultan Salad al-Din (Saladin; r. 1174-1193), and it is one of the very few records of the price of natron. He writes that during the late 12th century the cost of natron extraction was 2 dirhams per qintar, and with the market price in Cairo and Alexandria being higher at 70 dirhams per qintar (Rabie 1972, 85; Décobert 2003, 126). al-Qalqashandi, writing in *Kitab Subh al-a'shá*, further remarks that the price of natron had increased greatly during his lifetime, and had reached 300 dirhams in the early 13th century (Rabie 1972, 86). Whether this was short-term price fluctuations or a more permanent upward trend is unknown, however it certainly shows prices could achieve very high values and suggests a considerable profit was being made by the state. Ibn Mammâtî also notes that the annual demand for natron was around 30,000 qintar, or around 1350 tonnes, during the late 12th century (Rabie 1972, 85; 1 qintar = 45kg: Goitein 1967, 360).

To put the costs in perspective, a qintar of glass would require around 0.15 qintars of pure soda (Na_2O), if we assume soda content of typical Apollonia glass at around 15%. The molecular mass of Na_2O is 62 and contains two sodium atoms. Trona ($Na_2CO_3NaHCO_3.H_2O$), the most abundant soda containing mineral (Shortland 2004B), is a hydrated sodium carbonate with a larger molecular mass of 225. The weight of trona required for 0.15 qintar of soda can be calculated to around 0.36 qintars, more

than double the weight of soda (see calculation in Appendix L). Bear in mind this also does not take into account potential impurities such as sodium or potassium sulphates or chlorides which would increase the amount further. The costs of natron required to make one qintar of glass, therefore, is around 0.72 dirhams minimum at the extraction price of 2 dirhams per qintar, but was 25.2 dirhams at the late 12th century market price of 70 dirhams per qintar, and 108 dirhams at the early 13th century price of 300 dirhams per qintar.

How does this compare to the price of glass? The Cairo Geniza contains a contract describing a bulk order of glass for the setting up of a glass workshop (Goitein 1967, 365). The contract states that 108 qintars of red glass and 105 qintars of '*local*' glass was bought for 199 dinars. This equates to around 10 tonnes of glass. A dinar (gold coin) has an exchange rate with the dirham (silver coin) during the Fatimid period of between 36-40:1 (Goitein 1967, 359-60), giving a total cost of around 7164 dirhams for the glass (at 36 dirhams per dinar), giving a cost of 33 dirhams per qintar. This contract was written in 1217, just a few years after the natron rates quoted above. At 70 dirhams, the cost of the natron would have amounted to 2/3rds of the sale price of the glass. This is a large proportion of the price and leaves very little additional room for the costs of transport, labour, sand and fuel, not to mention profit. The price of natron during this period, therefore appears to render it unviable as a major component of glass. If the 300 dirham per qintar price is taken, then the cost of natron is over three times the sale price of the glass. These calculations demonstrate that the quantities of natron needed for glass are considerable and that the price during the 12th century was too high for glass production. It seems quite possible that at some stage in the 8th-9th century the cost of natron became prohibitively expensive for glassmaking. This was perhaps due to over burdensome taxation or government price hiking, however, it could also be due to the pressures of supply and demand.

As a final note, natron formation can be affected by relatively short-term changes in the weather. Cooler, wetter stretches will inhibit natron formation due to low rates of evaporation (Shortland 2004B), while during periods of drought the lakes will not fill up and the mineral content will not be replenished. There are some indications of unusual weather events during the Islamic period. Ellenblum (2012) details a

succession of cold, wet and drought periods which began with a severe cold spell in the mid-9th century, however these weather events are mainly recognised as occurring in the 10th and 11th centuries. During this period there were 27 failures of the Nile to flood (ibid, 3), and several spells of long lasting drought: 11 years between 1052 and 1072 and a 7-year drought between 1065-72. Although sporadic, these episodes would undoubtedly have affected natron production, however, the timing of these events post-date the cessation of natron use in glass.

9.3.4 Long-Term Factors Affecting Natron Use in Glass

There are a number of long-term trends that may have potentially affected natron use and extraction. The soda content of glass had fallen from a peak in the 1st century until production stopped in the mid-late 9th century. This trend in decreasing natron has been noted by several authors (Freestone et al 2000; Fischer and McCray 1999; Henderson 2002) and is illustrated in Figure 9.1 using a range of data from sites across the Mediterranean. The data has been split into glass considered to have been produced in the Levant (Figure 9.1a) and that from Egypt (Figure 9.1b) and encompasses an approximately 800-year period from the 1st to the 9th century CE. The figures demonstrate a distinct reduction in the quantities of natron over time, with both the Egyptian and Levantine glass displaying reduction in soda content, although the decreases are offset. For example, during this 800 year period the soda content of Levantine glass dropped by around 6% from 18% to 12% and Egyptian glass, over approximately the same timespan fell from 20% to 14%, also a 6% drop. Although these data are from just a few sites chosen for their accurate dating and superior data quality, it does illustrate a clear long-term trend towards falling natron content that emerged well before the Islamic period. This trend towards lower soda levels is indicative of a long-term, gradual pressure on the natron content, and therefore, likely the cost of glass. This could be a representation of the costs of raw materials versus the cost of fuel, for as natron increased in price the savings in natron would be greater than the increased cost of additional fuel requirements. It can be reasoned that this was only possible up to a point, as eventually melting temperatures would no longer be attainable and the costs of wood and natron would become prohibitively expensive.

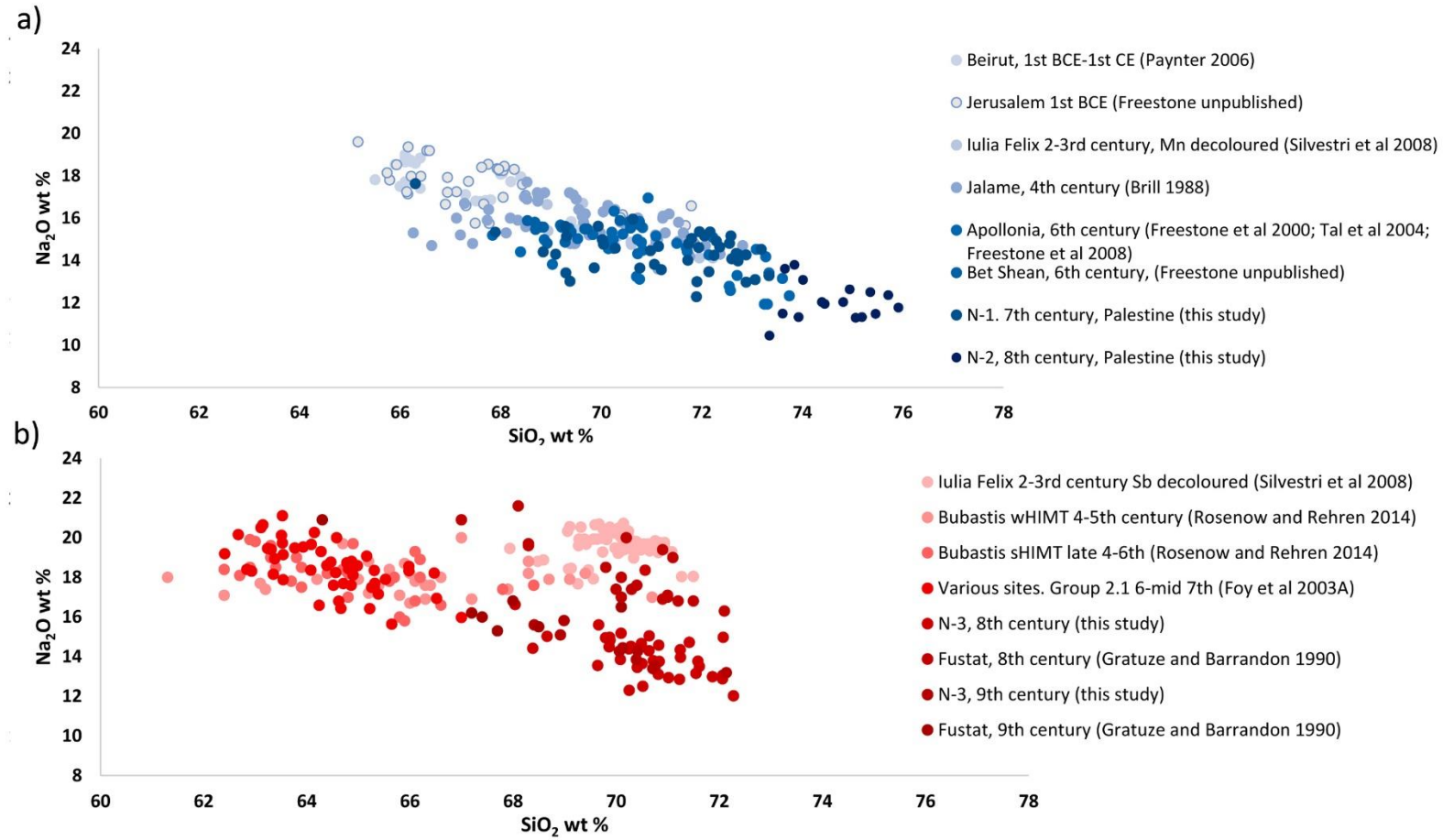


Figure 9.1. Image of soda versus silica for glass made in a) the Levant and b) Egypt. The glass is from a variety of well-dated sites covering approximately the 1st to 9th century. For both images darker colours represent later dates. The graphs demonstrate a trend of falling natron content through time for glass made at both locations.

There are two potential long-term factors that may have caused this trend. The first is climatic and the second is economic but may also be linked to cultural/social changes. Regional climate change would have the potential to reduce the quantities of available natron either over a prolonged period or permanently. This explanation has been proposed by several authors (Saguí 2007, 214; Picon and Vichy 2003; Picon et al 2008; Foy and Nenna 2001). Although the understanding regional climatic patterns is complicated and difficult to interpret, recent work by McCormick et al (2012) has been able to systematically assess climate patterns affecting the Roman and post-Roman world from the 1st century BC to 8th century CE using a significant number of data sources to highlight a series of general trends for the period. They demonstrated fluctuations in aridity and temperature in the Near East and Egypt, although there is no overall direction to this development, i.e. the regions do not become wetter or cooler over time. Looking to the 6th, 7th and 8th centuries it is noted that in the Eastern Empire there were falling temperatures and a decline in precipitation from around the 6th century that lasted until the 8th century (ibid, 205). They further note that it is *'possible… that cooler and less dry conditions spread within the 8th century'* (ibid, 202), hinting at a period of rainier and more humid weather mentioned (but not referenced) in Saguí (2007, 214). It is unclear how this affected natron extraction or how long cooler and wetter conditions persisted, but nevertheless an effect on natron formation is a possibility. However, it is also noted that there was a humid interval in the Near East from the 1st century BCE to 2nd century CE (McCormick et al 2012, 180, 183), and a generally cooler climate during the 3rd century (ibid, 185). So, while there are indications of a wetter, cooler climate in the 8th century, starting from around the 6th century, there are also periods of the same during the 1st century BCE - 2nd century CE, and again in the 3rd century. These two time periods have glasses with some of the highest levels of natron and do not demonstrate changes in natron use, apart from the general downward trend already stated. This suggests that there is no direct link between periodic climatic change and natron use. Nonetheless, reductions in natron output due to cooler, wetter climate in the 8th century cannot be categorically ruled out at this juncture.

The final process is economic and the action of supply and demand. Natron was a finite resource. Rabie (1972, 85) quotes Ibn Mammâtî writing in the late 12th-early 13th century that annual natron demand was 30,000 qintars, equating to 1350 tonnes. Contrasting the amounts required at this time to later average annual extraction figures suggest close similarity and a consistency of extraction quantities through the centuries. Annual figures for natron extraction in the 17th century is documented at 1632 tonnes (White 1932, 419). During the early 20th century 902 tonnes was exported in 1910, and 752 in 1911 (Lucas 1912, 29) – although these are export numbers only and do not include the quantities distributed within Egypt. These data suggest that the total extractable tonnage ranged between 1000-1600 tonnes per year. To put this in perspective, the estimated capacity of glass in the largest tank furnace at Tyre (37 tonnes) would have required over 13 tonnes of pure trona, not including impurities, equating to between 0.81-1.3% of the average annual natron output of Egypt for a single furnace. Multiple furnaces in Egypt and the Levant would have required a significant portion of the annual natron supply. Furthermore, glass was not the only use for natron. It has been utilised for many different purposes over the years: soap production, bleaching of thread and linen, curing of leather, incense production, purification ceremonies, dyeing of cloth, in medicines for humans and livestock (mainly for digestive complaints), in food preparation and in mummification (al-Hassan 2001, 64; Lovejoy 1986, 21-11, 27-29, 32; Bingley 1821, 128; Forbes 1965, 183; Lucas 1948,317-321; Rabie 1972, 85). A detailed study of the salt industry in Sudan indicated large-scale use of natron with livestock in the 19th century which was added to their diets for a variety of medicinal and health reasons. Estimates suggest around 10-15kg of natron was required per camel per year (Lovejoy 1986, 29) and 500kg of natron per thousand head of cattle, donkey and horses and half as much for sheep and goats (ibid, 12). While not all these applications are recorded during the Early Islamic period, it is clear that there are many potential uses for natron, all of which would have taken a proportion of the annual supply, and some, such as medicines and additives for dyeing, are likely to have been more profitable than the bulk quantities used by the glassmakers.

Of those uses listed above, two potentially large industrial uses for natron are apparent in the Islamic period, although the lack of quantification and paucity of sources makes this section more speculative than is ideal. The first is soap production. Natron is a soda source, and can be employed as an ingredient in soap (Doak 2009, 81; Lovejoy 1986, 27). Doak notes that hard soap production was pioneered during the Islamic period, manufactured using olive oil, alkali and natron (ibid, 81), and soap production became a well-established industry in Syria and also Spain during this time (Doak 2009, 81; al-Hassan 2001, 74). In the 19th century shea butter, natron and animal fat were ingredients in the making of hard soaps in the Sudan (Lovejoy 1986, 29). Natron, which is soda rich, would have been able to create hard soaps, while potash rich raw materials would produce soft soaps (Ashtor and Cevidalli 1983, 480). However, it must also be noted that soap could also be manufactured using plant ashes rich in soda or potash, as well as natron (al-Hassan 2001, 74; Ashtor 1992, 480) and the use of plant ash does appear more commonly discussed in relation to soap making (Ashtor and Cevidalli 1983). Nonetheless, Hiedenmann (2006, 41) notes that there was a close association between glassmakers and the soap industry in Abbasid period Raqqa, and there is a later period parallel in the competition between glassmakers and soap producers for ash chronicled in 17th century London (Godfrey 1975, 158-9). Therefore, it is possible that competition between the two industries for natron during certain periods may have existed.

There might also have been a cultural drive for increased soap usage in the Islamic period as Doak (2009, 81) comments that during this time an emphasis on the connection between cleanliness and health was developed. Furthermore, in Islam washing is obligatory before prayer (Insoll 1999, 32), although it should be noted that the use of soap is not specified, nonetheless, there may have been an uptake in soap usage due to an increased societal recognition of the importance of cleanliness.

The second major industry was the production of textile. Textile production, along with its associated activities, thrived during the Islamic period (al-Hassan 2001B, 135) becoming one of the largest industries in Egypt (Goitein 1961, 172-183). Textiles were high value products and their production came to employ a significant segment of the population (ibid, 172). During the Tulunid and Fatimid periods in particular textile

production underwent expansion, generating copious wealth in Egypt (Frantz-Murphy 1981, 296) and it was invested in by the Egyptian state during the Tulunid period (ibid, 281) enabling the industry to expand quickly. The use of natron is recorded in the washing of cloths, in dying and for bleaching (Forbes 1965, 183; Teresi 2003, 293). Lovejoy (1986) in particular records the use of natron with red and yellow dyes, and its requirement in the dyeing cloth and leather with indigo (ibid, 28). While these uses are not directly attested to during the Islamic period, the large-scale of textile production in the Early Islamic period, the various uses to which natron could be put, and the elevated value of the resultant products, meant that the textile industry would have been able to absorb considerable quantities of natron and afford the high price. As with the soap industry, it is likely that plant ashes could also be utilised in these roles, however, the superior quality of natron for these uses is emphasised by its specific use in the bleaching of linens in 17th century France (White 1932, 418). It is indisputable that natron was still in production after its use in glass ceased, and that it continued to be in demand and utilised for various industries even if the evidence is currently indirect.

9.3.5 Social and Cultural Factors

In addition to those 'push' factors which restricted natron availability, other cultural and societal factors may have been involved in the move to the use of plant ash flux. Henderson (2013, 253-260) states that the change to plant ash glass occurs at a high point in Islamic culture during the reign of Harun al-Rashid's (r. 785-809), a period of greatest development in Islamic material culture (Walmsley 2007 54; Brosh 2003, 319-20; Gorin-Rosen 2010A, 214; Milwright 2010B; Schick 1998). Henderson argues that not only were conditions conducive towards technological innovation but suggests that there was a switch by consumers towards distinctly Islamic technologies as Islamic culture matured (Henderson 2013, 259). One possible piece of supporting evidence is that plant ash glass tended to be mainly colourless, due to added manganese oxide, and so was visually distinct from natron glass, meaning it could be preferentially chosen by consumers. Colourless glass seems to have been preferred in the Abbasid and Fatimid period and it is seen in the highest quality cut glass vessels, as

well as much more frequently in other vessel types. Baker (2004) suggested that clear, colourless glass was highly prized, being associated at this time with ideas of purity, honesty and faithfulness (p8-9). However, a counter to this, is that clear, colourless glass was not an Islamic invention, nor was plant ash glass required for its production. Although typical Levantine and Egyptian natron glasses were normally aqua or bluish-green in colour, natron glasses of the Roman period were able to exhibit clear, colourless fabrics (Foster and Jackson 2010; Picon et al 2008; Silvestri et al 2008). This was facilitated by the addition of antimony or manganese oxides as decolourants, and there is no reason why manganese oxide could not be added to natron glasses of the period. Two samples of natron glass in group N-3 had added manganese oxide, of these, one had a colourless fabric (NS 6362-08) and was dated by form and context to the 9-10th century, perhaps demonstrating that there was a move towards colourless fabrics beginning even in natron production during the Abbasid period. It is unlikely that natron glass production would have been identified as a distinctly Byzantine technology, and it was perfectly possible to create colourless glass using natron. Therefore, the avoidance of natron glass and a preference towards plant ash glass of itself seems an unlikely factor in technological change when compared to economic factors.

9.3.6 Conclusions on the Demise of Natron Glass

It is concluded that production of natron glass discontinued due to a combination of short and long-term factors that led to restrictions in the availability of natron for glass working which culminated in the mid-9th century. It is suggested that less emphasis be put on the political instability, trade disruptions, and climatic and weather effects, although all these may have played small periodic roles, and greater emphasis be put on economic factors of cost, supply and demand. A number of other industries were in competition for the natron supply, and the higher prices they could demand for their products allowed them to invest more in purchasing the natron they required. The costs of extraction and trade were also amplified by the imposition of new taxes and government monopolies starting in the Tulunid period and continuing to the 15th century (Rabie 1972, 85-6). The gradual decline in the natron content of

glass exhibited through time is most likely an indicator of increasing price, which suggests rising demand from a finite resource. Glass, which was not a luxury item, could not increase its price indefinitely, being limited by what people were willing to pay. Lowering the natron content of glass was one solution, but had effects on the workability of the glass and increased fuel costs. There was also a limit to how little natron could be used. A number of potential markets for natron existed in other industries and for personal use that would compete for the finite annual natron supply and these may have become increasingly demanding over the centuries, particularly in the Islamic period. They may have been able to pay higher costs than the glass industry could maintain. The Egyptian government from the 9th century onwards (Tulunid, Ikhshidid, Abbasid and Fatimid) acted to control natron extraction, potentially restricting supply and further increasing the prices by taxation, while also endeavouring to maximise profits by a monopolisation of extraction and the establishing of new natron extraction sites (e.g. Lake Tarabiya). These events acted together to make natron no longer an economically viable raw material in the quantities required for glass production and consequently production shifted to the use of plant ash. As a final note, this situation was to pass, and by the late 18th century the production of glass lamps and phials in Egypt using natron glass is once again recorded (Brown 1799, 10).

9.4 The Origins of Plant Ash Glass Making Technology

From around the 10th century BCE natron started to be used in glassmaking in place of plant ash (see Chapter 4) and it was to become the principal flux in the Mediterranean and Europe. However, plant ash remained in use east of the Euphrates River and continued to be the raw material for Persian and Sasanian glass production (Whitehouse 2005, 67; Brill 2005). This continuity was recognised in analysis of Parthian (1st-3rd century) and Sasanian (4-7th century) glass (Sayre and Smith 1974; Sayre 1967, 152; Smith 1963). Sayre and Smith also identified that plant ash glass was used in the Islamic glass period, suggesting that plant ash glass was *'reintroduced'* from

Sasanian territories back into the Eastern Mediterranean (Smith 1963, 289). They suggested that the Islamic conquest and the bringing together of Byzantine and Sasanian territories enabled the transfer of plant ash technology (Sayre and Smith 1974, 65). Whitehouse equally noted a close similarity between Islamic and Sasanian glass, suggesting that Sasanian glass was a *'forerunner'* of Islamic glass technology. These sources suggest that Islamic plant ash glass in the Eastern Mediterranean and Levant was descended from Sasanian glassmaking technologies and traditions; but how true is this? Is Tyre production an off-shoot of Sasanian technology or is it a melding of Byzantine and Sasanian practices? What is more, could Tyre production be an adoption of an Eastern Mediterranean plant ash technology and not related to Sasanian technology at all?

This section will discuss the potential origins of Islamic plant ash glass technology in the Levant. Two paths to innovation are considered: firstly, a transfer of Sasanian technology from the East, this is the generally preferred route (Henderson 2005A; 2013; Whitehouse 2005; Smith 1963), and secondly the development and adoption of an already understood technology in the Eastern Mediterranean which had lain almost entirely unused.

9.4.1 Sasanian Origins of Plant Ash Technology

One method for investigating the transfer of technology is through the identification of specific traits within a technology – what Lechtman called *'technological style'* (1977) but which are also termed *'technological traditions'* (Van der Leeuw et al 1991; Tite and Sillar 2000). These are characteristics that become associated with cultural choices or preferences, which alongside material or ecological determinates create a technology specific to a particular culture. White and Hamilton (2009) in their investigation of the origins of bronze metallurgy in Thailand commented that the technology represented a *'complex technological system'* in which a number of interrelated technologies were required to recreate the metalworking processes. Sasanian glass production would likewise have an associated set of inter-related technological traditions based on choices that would make production distinct from

Roman/Byzantine practices. The framework of technological traditions has been used successfully to trace the origins of technologies, for example, in the investigation of the origins of gilding techniques in the Andes (Lechtman 1977). It is theorised that if production at Tyre showed traits common to Sasanian glass manufacture, then a technological link might be implied.

Table 9.1 compares Eastern Mediterranean glass production against Mesopotamian/Sasanian glass production. Eastern Mediterranean glass production is represented by data from the primary production sites of Egypt – Wadi Natrun and Beni Salama (Nenna 2015) – and Syro-Palestine – Jalame (Weinberg 1988 and Gorin-Rosen pers. comms.), Apollonia and Bet Eli'ezer (Gorin-Rosen 2000), Tyre (Aldsworth et al 2002) and Raqqa (Henderson et al 2004). The data for Sasanian production is much more scarce. Around 10 production sites have been identified in Iraq from surface finds, and the quantities of waste material has indicated a large-scale industry but no detailed study has been conducted (Brill 2005; Simpson 2014). As mentioned in Chapter 4, the Raqqa Type 4 production type displays remarkable compositional similarity to Sasanian production and has been suggested as possibly made using Sasanian traditions by Sasanian workers (Simpson 2014, 204). Therefore, this group and its associated production waste, will be used as a parallel for Sasanian glass production, although noting that this is not conclusive link. Finally, Nishapur and Samarran glass, of which the evidence is only from the glass analysis itself, was also used (Brill 1995; Wypyski 2015). The table compares broad categories: furnace capacity, stages of process, type of plant ash flux, compositional standardisation and use of manganese oxide as a decolourant.

Although direct information on Sasanian glass production is scant, the table nonetheless presents enough indirect detail to begin to define Sasanian glassmaking technology. Compositionally, Mesopotamian glasses use plant ash flux high in MgO and low in CaO, this is different from Eastern Mediterranean glass types, however, this is most likely ecologically determined through the types of plant species and local geology, and is unlikely to be representative of technological choices, and so will not be used to make distinctions between glassmaking technologies.

Table 9.1 The key characteristics of glass production from different localities dating from the Roman to Islamic period.

	Eastern Mediterranean						Mesopotamia		
Location	**Wadi Natrun/ Beni Salama[1]**	**Jalame[2]**	**Apollonia/ Bet Eli'ezer[3]**	**Raqqa Type 1[4]**	**Tyre[5]**		**Sasanian**	**Raqqa Type 4[4]**	**Nishapur/ Samarra[5]**
Date	1st-3rd	4th	6th-7th	late 8th /early 9th	10th-11th		3rd-7th	late 8th/ early 9th	10th
Capacity	13-22 tonnes	8 tonnes?	8-9 tonnes	5 tonnes?	13-37 tonnes		unknown	5 tonnes?	unknown
One or two stage process	1	1	1	1	1		2?	2?	unknown
High Ca/High Mg Flux	n/a	n/a	n/a	High Ca	High Ca		High Mg	High Mg	High Mg
Compositional Range	narrow	narrow	narrow	narrow	narrow		broad	broad	mixed
Added manganese	sometimes	sometimes	no	yes	yes		no	sometimes	sometimes
Addition of de/colourants at primary stage	yes	yes	no	unknown	yes		unknown	unknown	unknown

1 Nenna 2015; 2 Weinberg 1988; Gorin-Rosen pers. comms.; 3 Gorin-Rosen 2000; Freestone et al 2000;
4 Henderson et al 1999; 2004; Khali and Henderson 2011; 5 Aldsworth et al 2002; Freestone et al 2002; 5 Brill 1995; Wypyski 2015

Compositional standardisation of Mesopotamian glasses is generally lower than Eastern Mediterranean glasses. Many of the recognised groups exhibits relatively large variance in many oxides of the silica source (see Table 4.1; Figure 4.6). Although, some causes of this may be geological, and due to natural variations in the sands used (as observed in the wide variation of HIMT glass; Nenna 2014), it might also reflect manufacturing practices or indicate a less strict adherence to recipes, and this would be a choice. The use of smaller tank furnaces could cause more variation between raw material batches, as would production dispersed over a larger geographic area. Evidence for the latter has been demonstrated by isotopic studies of Sasanian glass (Ganio et al 2013) which identified several isotopic sub-groups within the groups already identified by Mirti et al (2008; 2009). This suggests that production was carried out at more than one locality, although within the same geological region, implying a spread of production locations, thus demonstrating a disparity with plant ash glass from the Eastern Mediterranean which tended to use quite tightly defined recipes, such as Raqqa Type 1 and Tyre.

In terms of furnace size, a capacity of around 5 tonnes is estimated (Chapter 4) for the late 8-early 9th century furnace identified by Khalil and Henderson (2011) at Raqqa, although whether these are typical of Sasanian production is not known but the quantities and types of waste material found during surface surveys do support the use of tank furnaces in Sasanian contexts (Simpson 2014, 205 and references therein). Plant ash glass production at Tyre also used tank furnaces, with capacities ranging from 13 to 37 tonnes, this was larger although this furnace dated later than the Raqqa example.

Another aspect is the use of fritting stages. Material interpreted as frit was found in association to Raqqa Type 4 glass (Henderson 1999; Henderson et al 2004; see Chapter 4), as well as an area interpreted as a possible fritting oven. Only a single fragment was analysed although more were present, and although the this interpretation as frit is not fully confirmed, if true, it would suggest that Raqqa Type 4 was manufactured using a two-stage process. This corresponds with the finding of frit-like material of Sasanian date from Tell Umm Jirin, Iraq, also interpreted as frit (Brill 2005, 71), although Brill notes that it could be unreacted batch. Quantities of unreacted batch are

noted from ethnographic studies of glass making using large furnaces, so this is a possible occurance (Sode and Kock 2001). Nonetheless, if true, this evidence potentially suggests that Sasanian glass production may have used a fritting stage, not used in production at Tyre or Eastern Mediterranean sites.

The use of manganese oxide as a decolourant also underscores further differences between Tyre and Sasanian practices. The Sasanian glass analysed by Mirti et al (2008; 2009) does not contain added manganese oxide. In the Islamic period, using a cut off of 0.2% (2000ppm) for deliberate addition as suggested in Chapter 7, the Nishapur Colourless glass is found to have a low but consistent content of manganese oxide. For the Nishapur Coloured and Raqqa Type 4 groups deliberate addition of manganese oxide is more infrequent, present in around 50% of the vessels (Henderson et al 2004; Brill 1995). Further investigation of Raqqa Type 4 data does not link manganese oxide use to either of the end-members (high Mg/low Al and low Mg/high Al; see Chapter 4), however, there is some correlation with glass form – manganese oxide decoloured glass is used for windows, vessels, furnace glass and production waste (Henderson 1999; Henderson et al 2004). Glass without manganese oxide is utilised in vessels, mould blown bowls and bangles, but is not a component of furnace glass or waste. It suggests that the manganese-free glass was imported and the glass with added manganese was produced at Raqqa. This potentially indicates that the addition of manganese oxide was an Islamic technique that did not originate in Sasanian territories. Syro-Palestine plant ash glass (Tyre, Raqqa Type 1, Banias and Group P-2a), on the other hand, all contain added manganese oxide, implying that this technique came from the Eastern Mediterranean and came to be used at Raqqa, but did not originate in Sasanian practices.

To summarise, the use of manganese oxide as a decolourant in Tyre but not Sasanian glass, and the dispersed nature of production organisation, as well as the potential but unverified use of a fritting stages in Sasanian glassmaking but not in Tyre glassmaking tentatively suggests that Sasanian technology was not the origin of plant ash technologies used in the Eastern Mediterranean Islamic plant ash production.

9.4.2 Plant Ash Glass as an Eastern Mediterranean Technology

It is possible that plant ash glass technology was not transferred at all but was already known in the Eastern Mediterranean. During the Roman period, as reported by Pliny, it was understood that the burning of certain trees would produce a *'nitrous ash'* – i.e. an ash like nitre/natron (*Nat Hist* 16.11 in Bostock and Riley 1893). Pliny also records plants being used as detergents and for bleaching clothes (*Nat Hist* 20.79 in Bostock and Riley 1893; Ashtor 1992, 481) suggesting that various properties of plant ashes were understood, although there is no direct mention of the burning of halophytic plants to make soda. While natron glass dominants production during the Roman period, glass with a plant ash component is present, mainly consisting of coloured types. One group is a specific emerald green glass, relatively well spread in its distribution, but noted for its high flux content suggesting the addition of a plant ash component (Henderson 1996; Jackson and Cottom 2015 and references within). Plant ash glass examples are also noted from coloured mosaics (Nenna and Gratuze 2009). Other examples are found from Egypt; several plant ash glass vessels were found dating to the 1st-5th centuries at Bubastis (Rosenow and Rehren 2014). The flux content has the low MgO/high CaO typical of Islamic glass from Eastern Mediterranean sources and not Parthian or Sasanian glass. Furthermore, the TiO_2 and Al_2O_3 contents are within the ranges of other Egyptian glass, suggesting local production. Four further samples, dating to the 3rd century, were found at excavations at the Wadi Natrun (Picon et al 2008) and similarly displayed a low MgO and high CaO content. The lime is very high (9.5-16.3%), while typical lime contents of the natron glasses was 1-3% depending on the group (ibid, 38), suggesting plant ash was added directly to the low-lime sand. This range of examples from Roman period contexts suggest that plant ash glass was being produced in small quantities in Egypt and possibly elsewhere, for small scale and sometimes specific uses. If this production continued into later periods, it would suggest a possible origin for the plant ash technology utilised in the Eastern Mediterranean. Furthermore, the Roman plant ash glasses from Egypt contained manganese oxide, a ubiquitous feature of Islamic plant ash glass in the Eastern Mediterranean but not present in Sasanian production.

There are also similarities in production between the Roman-Byzantine natron industries in Egypt and Palestine and in production at Tyre. The scale of production at Tyre with several tank furnaces of many tonnes capacity, is similar to Roman production at the Wadi Natrun, with furnaces estimated at capacities of between 13-22 tonnes, and similar, but larger than Byzantine production at Bet Eli'ezer and Apollonia, at around 8 tonnes. The clear separation between primary and secondary production at Tyre is another Roman-Byzantine tradition, as is the concentration of production at a few large sites, and the use of manganese oxide as a decolourant. Manganese was added to all the glass analysed from Tyre (Freestone 2002), although it is not seen in 6th-8th century production from Apollonia and Bet Eli'ezer (Freestone et al 2000). It is recorded in slightly earlier production, and was used to decolour Roman glass at the Wadi Natrun (Picon et al 2008) and is recognised in Roman glass from various sites around Europe (e.g. Foy et al 2003A; Silvestri et al 2008; Foster and Jackson 2010). Manganese oxide was also added to HIMT glass produced in Egypt around the 5th-6th century (Freestone 2003; Freestone et al 2005; Nenna 2014) and is present in some of the glass analysed from Jalame, dating to around the late 4th century (Brill 1988). In later years, it is also evident in 9th century glass of Egypt II type, analysed as part of this study. It suggests that manganese oxide use in the glass from Tyre (and Raqqa) was a continuation of Roman and Byzantine natron glass practices.

A direct link between glass production at Tyre and the glass working regions of Palestine are supported by documentary evidence. Le Strange (1890, 333) quoting Yaqut (1179-1229), a well-travelled geographer writing in the early 13th century, writes of Akko that *"All of the artificers of the land lived here. Then Hisham moved them all to Tyre."* Hisham was caliph from 724-743, and this statement has been interpreted by Engle (1973, 7) as implying that the craftsmen of from Akko were moved at this time. Akko is located on the bay of Haifa, an historic glass making region close to the mouth of the Belus River where glass making sands were collected since ancient times and near to the production sites of Jalame and Bet Eli'ezer, and therefore these craftsmen likely included glassworkers. The movement of glassworkers from Akko in the mid-8th century would have been a mechanism in which glass-working knowledge, as well as

the workers themselves, could have been transferred, and this may have been the event that triggered glass production at Tyre.

The idea that plant ash glass technology was adopted as a technology within the Eastern Mediterranean is also supported by sample chronology. There were three compositional types of plant ash glass that appeared in the late 8th century: two with similarity to Tyre (P-1); two thought to be Syrian production (P-2a); and two (outliers) possibly of Raqqa Type 4. Of these, two samples (Tyre type and a Raqqa Type 4) were could have dated as early as the Umayyad period (early 8th century). A further sample dating to the same period was a mix of Tyre and Egyptian glass. The earliest plant ash glass, therefore, is not dominated by production of a Sasanian type but contemporary with 'local' types from Syria and Tyre. The chronological evidence suggests that some of the very first plant ash glass shared compositions with Tyre production, appearing soon after the suggested movement of glassworkers during the reign of Caliph Hisham. If plant ash technology was being transferred from Sasanian territories, it would be assumed that a location nearer the origin would employ the technology first, however, production at Tyre appears to be contemporaneous with production at Raqqa. Therefore, rather than technological transfer from Sasanian territories it is more likely that this was a process of technology adoption, driven by strong demand for glass and lessening natron glass production in Palestine. However, why was this technology adopted in Tyre and Syria but not Palestine? It is possible that only Tyre had the correct raw materials available, and the evidence for this comes from the Bet She'arim glass slab.

The Bet She'arim glass slab is an approximately 9 tonne single block of glass found abandoned inside a Byzantine cistern. The glass was originally dated to the 4-7th century (Brill and Wosinski 1965; Brill 1967) and found to be devitrified due to the anomalously high lime content at 15% (Brill and Wosinski 1965). It was concluded that the glass did not fully form because the temperature required to melt and react a glass of that composition would have been too high. Freestone and Gorin-Rosen (1999) reassessed the origins of the slab, establishing that while the alumina, iron oxide and titania contents are more or less the same as a typical Palestinian natron glass, the slab contained magnesia and potash at levels more typical of plant ash glass. Freestone and

Gorin-Rosen argued that the slab was likely a mix of plant ash flux with a typical sand used in natron glass production. The glass also contained added manganese oxide. They suggested that this slab was actually a product of two different traditions – an Islamic plant ash tradition alongside Byzantine natron glass making traditions. They further suggested a post-Byzantine date of the 9th century, this was after the cistern was no longer in use and during a period where Islamic plant ash glass was in production (ibid, 113).

While the slab appears to be a melding of two different glassmaking traditions, it is not likely to be an experimental step in the invention of plant ash glass. From the raw materials (plant ash flux and use of manganese oxide) and the scale, it appears that the processes of plant ash glass production was known to the glassmakers. Rather it was an attempt to match the known raw materials of plant ash glass with local sands. Therefore, the slab fits into the narrative suggested above, that there was a push to adopt plant ash glass technologies within Palestine, that the raw materials and technology were already known in the region, and this glass represents an attempt to combine two different sets of raw materials. It may signify a final attempt to revive or prolong the Palestinian glass industry. However, the sands in Palestine contain too much lime for a glass to be produced, it could be that none of the sands in the region were suitable and this resulted in the demise of the industry in Palestine. This slab may explain why the plant ash glass industry managed to flourish in Tyre but was unable to take hold in Palestine despite plant ash technology being known.

9.4.3 Origins of Plant Ash Glass Summary

Palestinian glass supply in the Abbasid period was dominated by production from Tyre. Although evidence is limited, there appears to be less to link production to Sasanian practices than there is to suggest that production at Tyre was a continuation of a long history of glass production in the Eastern Mediterranean. In terms of the organisation, the scale, and connections to earlier Roman but also later Byzantine practices in Egypt in the use of manganese oxide, definite similarities are apparent. This evidence is supported by the chronology, which suggests that production at Tyre

was contemporary with Raqqa and that production may have followed the movement of glassworkers from Akko to Tyre during the reign of Caliph Hisham. The evidence from Bet She'arim is here interpreted as an attempt by glassworkers of Palestine to find a viable sand source for use with plant ash, and its failure might explain why plant ash glass production did not continue in Palestine.

9.5 Production Organisation and the Supply of Plant Ash Glass as Seen from Palestine

One of the aims of this project is to understand how the organisation of the glass industry within Palestine changed with the use of plant ash flux. Did the centralised production model of the natron glass industry continue or, with the widespread availability of halophytic plants, did production sites become more dispersed? There is also the wider question of glass supply, and how that shifted with the end of natron glass production in the Levant and Egypt. This section will look at the developments in the supply of plant ash glass, and investigate the changing centres of glass production as they appear in the Abbasid and Fatimid periods.

9.5.1 Evidence for Centralized Production

There is a significant body of evidence demonstrating the centralised nature of natron glass production during the Roman and Byzantine periods, as summarised in Chapter 3. The natron glass identified in this study comprised four recognised glass types, three of which have evidence for their trade and use as raw glass in Palestine through archaeological finds at workshop sites in Late Byzantine Apollonia (Tal et al 2008), Dor and Bet Shean (Freestone et al 2000), pre-Islamic Ramla (Freestone et al 2008A) and an Islamic 8th century site at Tel Aviv (Freestone et al 2015). The evidence presented in this thesis alongside that of the workshop at Tel Aviv and production at Bet Eli'ezer (Gorin-Rosen 2000) suggest that the centralised production model continued unchanged after the conquest. Only the two samples of Egypt I type (N-4) had no evidence for its trade as raw chunks. (A trade in Egypt I type vessels has been

suggested from Cyprus (Ceglia et al 2015, 220). Of the 8 outlier natron vessels, only two samples (AH 3746-03 and RAM 5947-27) had a composition that suggested mixing outside of the known groups and which might attest to at least one additional production centre, but of these, one sample had high levels of antimony that might indicate a Roman type. The natron glass indicates a small number of primary production sites conforming to the accepted centralised production model.

The evidence for centralised production with plant ash glass in the Islamic period is much more mixed. Henderson et al (2016), based on his analysis of relatively small quantities of glass from a large number of sites in Mesopotamia, Syria, Palestine and Egypt, suggested that Islamic production was based around broad regional compositions with smaller *"production sub-zones associated with large cosmopolitan urban hubs"* (p142). He goes on to suggest that *"decentralised production occurred over a period of c. 800 years"* in the Levant (ibid). The results of this thesis support some aspects of Henderson's conclusions, however, the results do not agree that centralised production ended in the Levant during the Islamic period, although the picture is more complex than natron production, with the data suggesting aspects of centralised and decentralised primary production and the trading of vessels over long distances during the Abbasid and Fatimid periods.

The supply of glass in 9th-13th century Palestine is dominated by Tyre production. Of the 151 plant ash glasses identified (including outliers) two-thirds (102) were made of glass from Tyre. There were lesser quantities of four more identified glass types: P-2 (a & b) of unknown, possibly Syrian origin, the latter only appearing in the 11th-13th century; two Mesopotamian types, P-3 and P-4, mainly confined to the 10th and 11th centuries; and 9 outlier samples suggesting at least three other production types. This demonstrates more diversity and a larger number of production sites than the natron glass. Primary production at Tyre was large scale; a firing of all four furnaces using the capacities suggested by Aldsworth et al (2002, 66) would produce 79 tonnes of glass, this could theoretically produce over 1/2 million vessels at 150g per vessel. Each of the furnaces shows signs of multiple firings, so the capacity over the lifetime of the furnaces was much higher, and these are unlikely to have been the only furnaces operating in the vicinity. The industrial scale and lack of any associated secondary

production suggests that not only was this glass for export, but that the glass was traded as raw chunks. This premise is supported by the context and forms of the samples analysed from Palestine.

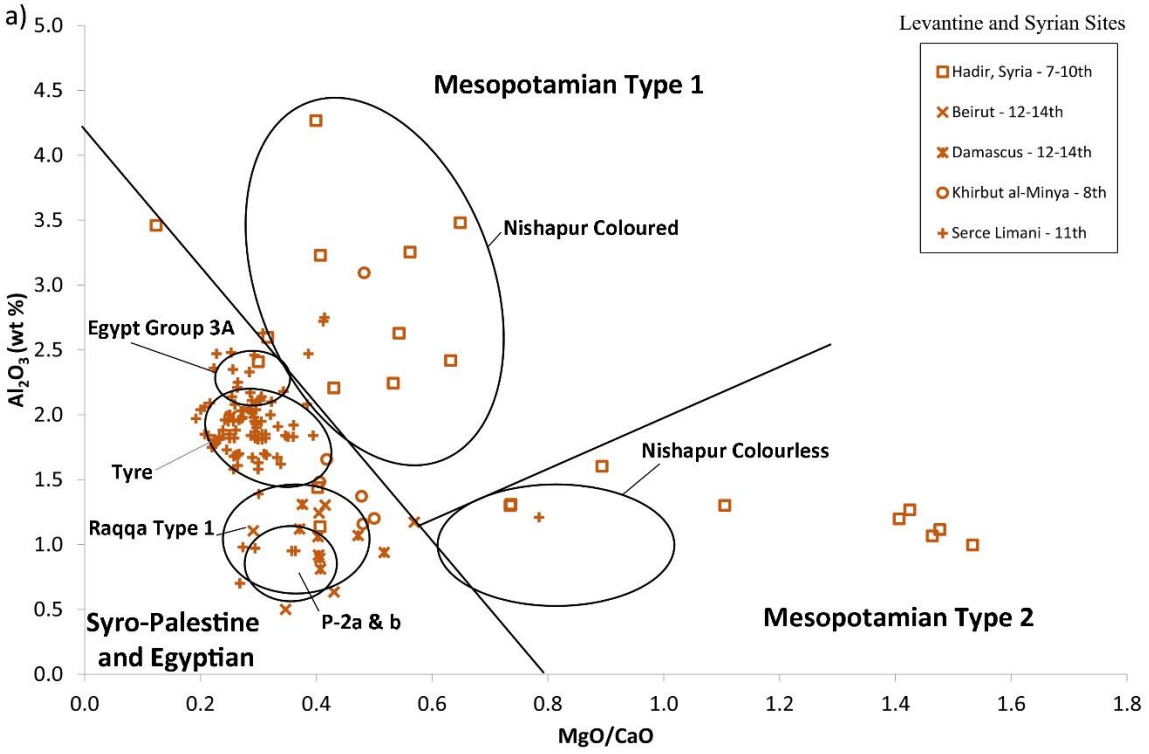
Tyre type glass (P-1) appears to be a common and widely available type in Palestine and is the most dominant type in the 9th-11th centuries. Local production is attested by a number of factors; it is the only plant ash group to show significant quantities (20%) of recycled examples. This implies that Tyre production made up the pool of glass cullet in use at workshops and that it formed the bulk of the glass in general circulation. It is the only plant ash glass type recognised as having been through the stages of use, discard, cullet and re-melting. Although the number of recycled examples is lower than natron glass estimates, possibility suggesting that larger quantities of fresh glass was entering into circulation during Abbasid times than in the Umayyad period, it is also possible that recycling in plant ash glass is underestimated due to the higher background quantities of colourant elements in plant ash glass.

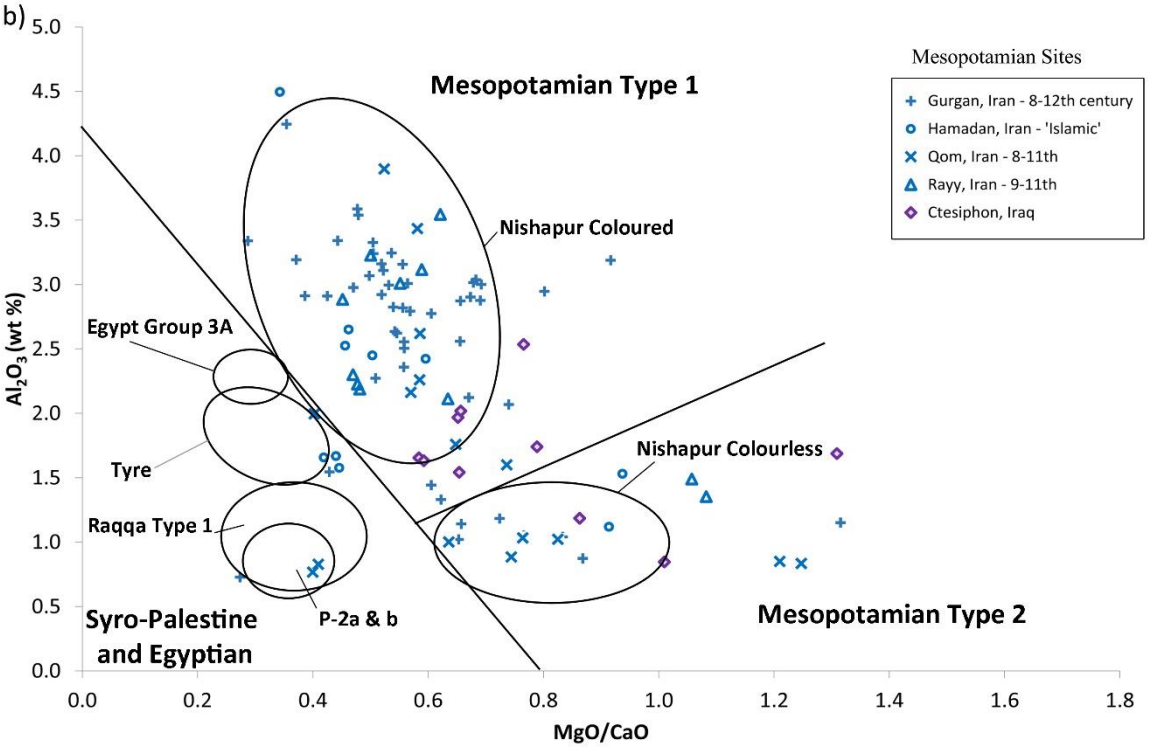
Local production has also been implied from the utilitarian forms of much of the P-1 vessels and from their lower quality workmanship. Examples include various vessels from Tiberias (e.g. TIB 5583-12, -23, -30; Gorin-Rosen pers. comms.), Caesarea (e.g. CEA 6194-03, -09; Gorin-Rosen pers. comms.), and Ha-Bonim (e.g. HB 3232-13, -19, -21; Katsnelson pers. comms). Some higher quality wares were identified and these are discussed later. Furthermore, the finding of unique forms at some sites is also evidence for the existence of localised glass working. This was found at Bet Shean, where some vessels dating to the Abbasid-Fatimid period had no parallels at other locations (Hadad 2005, 78).

The transport of large quantities of glass from Tyre to Fustat is recorded in the Cairo Geniza which reports the purchase of 37 bales of glass in 1011 from three Jewish ‘firms’ (Goitein 1967, 421; see also Whitehouse 2009, 506 and Carboni et al 2003, 148). 1 bale is equivalent to 500lbs in weight (Goitein 1967, 335) giving a calculated total of around 9.25 tonnes (1lb = 0.45kg). This is a considerable consignment but Carboni (2003) notes that there is nothing to suggest that this quantity was unusual (p148). Although it is not recorded whether the glass was raw or as cullet the movement of large quantities of raw glass during this period is also attested by the Serçe Limanı

shipwreck, found off the coast of Turkey and thought to have been travelling northwards to the Byzantine territories. Dating to 1025, it was found to contain 3 tonnes of glass, 2 tonnes as raw chunks and 1 tonne as cullet, mainly as moils suggesting it came from a glass workshop (Bass 2009). A selection of glass from the Serçe Limanı was analysed by Brill (2009), and the data is presented in Figure 9.2a in comparison with data from a range of other sites in Syria and Palestine. Labelled circles have also been added marking the different production and compositional groups as identified in from literature data in Chapters 3 and 4. The image demonstrates that the vast majority of both the Serçe Limanı material share a close compositional similarity with Tyre production, as was first identified by Brill (2009, 480), and therefore, might be thought of as produced in close vicinity to Tyre. These two pieces of evidence, along with Palestine compositional and typological data, demonstrate a trade in raw glass from Tyre to Palestine during the Abbasid and Fatimid periods and also that this glass was being traded to Egypt and the Byzantine Territories during the 11th century.

Quantities of Tyre type glass and some Syrian types have also been identified from other locations. Figure 9.2a, b, c present data from consumption sites in Syria and Palestine, Iran and Mesopotamia, and Egypt, respectively. The glass from sites in Egypt (Fig 9.2c), which contains vessel data from Raya and Wadi al-Tur dating to the 9-11th centuries, demonstrates a significant amount of glass of possibly Syro-Palestinian composition (Kato et al 2010A). However, it must be noted that the use of portable XRF on unpolished samples means there is greater inaccuracy in the results compared to other techniques. Nonetheless, they identified several compositional groups; Kato's Group PA-1a was identified as Raqqa Type 1 (ibid, 1392), and falls into that region of Figure 9.2c, a second group, PA-1 colourless, containing higher alumina (av. 1.6) and lower titania (av. 0.06), clusters within the Tyre region of Figure 9.2c, although these vessels were recognised by Kato et al (2010A, 1393) as an unknown Egypt/Mediterranean type. Some samples from Fustat (Kato et al 2010b) also fall into the region of Tyre. Tyre type glass is, in addition, identified as a sub-group within Gratuze and Barrandon's Group 3 (Gratuze and Barrandon 1990), as discussed in Chapter 4.





Figures 9.2 a & b – caption overleaf.

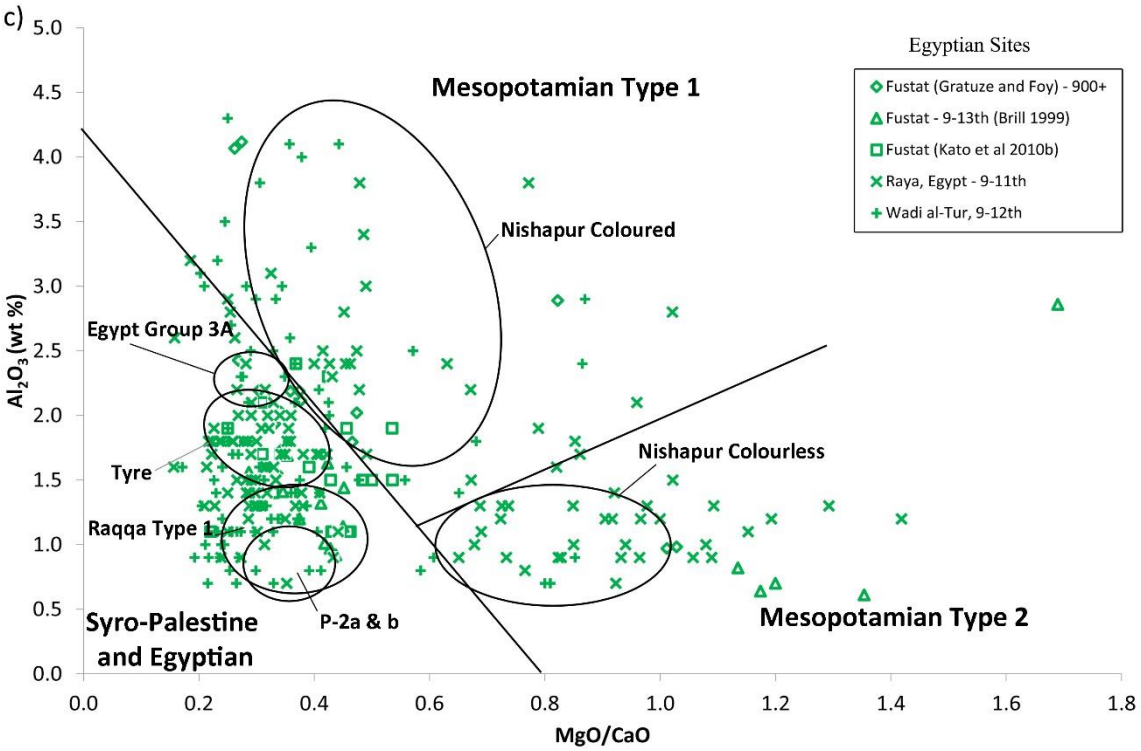


Figure 9.2. Glass data from various consumption sites from the 8-14th centuries. Principal known groups circled as in Figure 7.4a (Chapter 7). The data is separated by location; a) Syrian and Palestinian glass from Hadir, Syria (Gratuze and Foy 2012) and Beirut, Lebanon, Damascus, Syria, Khirbut al-Minya, Israel (Henderson et al 2016); b) Iranian glass from Gurgan, Hamadan, Qom and Rayy (Lankton pers. comms. of samples from Brill 1999A) and Mesopotamia glass from Islamic period Ctesiphon, Iraq (Henderson 2016); and c) Egyptian glass from Fustat (Gratuze and Foy pers. comms; Brill 1999; Kato et al 2010B) and XRF data from Raya and Wadi al-Tur (Kato et al 2010A).

In Mesopotamia, four samples of 'Levantine' glass were identified from Nishapur (Henderson et al 2016, 142) and a number of vessels from Nishapur and Samarra have been recognised by Wypyski as Levantine (2015, 130, 132), which were labelled as 'Type D'. In Figure 9.2b, a few samples from Qom and Hamadan also suggest a Syro-Palestine origin, possibly from Tyre or of Raqqa Type 1.

The samples described above demonstrate a relatively widespread distribution of glass from Syro-Palestine. However, was this glass traded as vessels or as chunks? The four pieces of Levantine glass identified at Nishapur (Henderson et al 2016) had threaded (trailed) decoration, which Henderson suggested was a Levantine regional specialisation, implying the movement of the finished vessels. At Raya, on the other hand, the majority of the Syro-Palestine glass types are noted as undecorated,

domestic types (beakers, bottles, lamps), and are therefore less likely to have been imported as vessels and more probably transported as raw chunks and shaped at Raya/Wadi al-Tur. However, a number of lustre decorated types were also identified. By style they were indicative of Egyptian production (Kato et al 2010A, 1393), but noting here their compositional similarity to Tyre glass, it could potentially suggest the trading of Syro-Palestine glass to Egypt, shaping in Egypt, and onward trade to Raya, although these could also be unidentified Egyptian types of a similar composition.

The range of evidence presented here strongly suggest that a centralised production model continued to operation for a significant percentage of the glass in circulation in Palestine and across the wider Eastern Mediterranean to Egypt and also Byzantine territories. This principally involved production at Tyre, of which there is the greatest evidence, but there is also some evidence for the trade to Raya of Raqqa/Syrian glass types. Lesser quantities of Tyre glass, perhaps as vessels, were also travelling to Iran and Iraq.

9.5.2 Trade in Glass Vessels

The Mesopotamian glass groups (P-3 and P-4) are more characteristic in their forms, fabric and decoration and suggest an alternative model of supply to Palestine. P-3 and P-4 amount to 18 and 10 vessels respectively, making up 12% and 7% of the plant ash glass. As demonstrated in Chapter 7, the P-3 and P-4 groups are synonymous with the Nishapur Colourless and Nishapur Coloured groups as identified by Brill (1995). They further equate to Wypyski's Nishapur and Samarra Types A and B respectively (Wypyski 2015). Moreover, they also show compositional similarities to Sasanian types as demonstrated in Chapter 4, which has led to the suggestion of a Mesopotamian origin for potentially both types by Wypyski (2015). The production of Nishapur Colourless (P-3; Samarra Type A), in particular, has been proposed to originate in the vicinity of Samarra (Wypyski 2015, 136).

In addition to compositional similarities to Sasanian glass, there are a number of other pieces of evidence which link the Nishapur glass to a possible Mesopotamian origin. Firstly, the Nishapur Colourless glass has a composition within the range of Samarra

Type A, suggesting it is a higher purity sub-type of this group (Wypyski 2015, 136). It suggests the superior quality glass was traded over larger distances, and the lesser quality glass was not. Secondly, the same forms with the same decorative techniques are found at both sites (Kröger 1995, 6, 36-37), indicating close links in form and style in the vessels produced. Kröger comments that in some vessels there are *"instances where the designs from the two sites seem indistinguishable"* (ibid, 6). Thirdly, there are also no glass working remains at Nishapur (Kröger 1995, 20) but there are at Samarra (Northedge and Falkner 1987). Finally, there are large quantities of Mesopotamian pottery at Nishapur (e.g. opaque white ware; see Wilkinson 1973, 179), which demonstrates the movement of goods from Mesopotamia to Nishapur. A fuller discussion of this is provided in Wypyski (2015) but this evidence offers a convincing argument for the glass at Nishapur being potentially of Mesopotamian production and possibly from Samarra. Lamm (cited in Hadad 2005, 67) also thought that wheel-cut types originated in Iraq and were transported to Iran. Note however, that this contrasts with the conclusions of Kröger and Henderson et al who suggest that the glass was produced at Nishapur (Kröger 1995, 37) and exported to Samarra (Henderson et al 2016, 142).

Group P-4 (Nishapur Coloured/Samarra Type B) is much less widely represented at Samarra than Nishapur Colourless/Type A. Wypyski comments that of the two types, the Nishapur Coloured group is more likely to have been locally produced at Nishapur due to the lower quality of vessel and greater abundance (Wypyski 2015, 135), although, it is equally possible that raw glass was traded and the vessels only shaped in Nishapur. This glass type is similar to identified Sasanian types (Chapter 4) which are noted to have a wider compositional spread and which might represent a range of production centres, possibly within Mesopotamia but depending on the composition of available raw materials, might include areas of Iran. Figure 9.2b demonstrates that Iranian consumption sites are dominated by the Nishapur Coloured glass type, further suggesting that this was a more common, widely produced glass. However, the P-4 vessels are cobalt coloured and it has been noted that cobalt was not used to colour any of the ceramics produced in Nishapur (Wilkingson 1973, 186), possibly giving additional evidence that this glass was more probably produced in Mesopotamia

rather than Northern Iran. The P-3 and P-4 groups both date within the period of occupation of Samarra, which was founded around 834-5 CE. It was abandoned as a capital in 892 but continued to be occupied into the 10th century. Neither glass group appeared to continue after the 11th century.

The question of whether these groups were traded as raw glass or as vessels can be investigated by considering their vessel forms. The P-3 group is almost exclusively composed of high quality, colourless fabrics, and were made of glass with no signs of recycling. Almost all are bottles (one bowl, two unidentified) and most are decorated (twelve wheel-cut and two mould blown square bottles). The fabric quality and decoration suggest that the vessels were relatively high status items (see Figure 9.3 a-e). The Nishapur Colourless group of vessels also had a large number of wheel-cut examples (Brill 1995), as did those of Samarra Type A (Wypyski 2015; 127). It suggests that this specific glass type was used to produce higher quality wheel-cut and mould blown glass. There are type parallels between the vessels from Nishapur and Samarra (Kröger 1995, 36-37) and those from Palestine, for example, miniature bottles from Ramla and Bet Shean as identified by Hadad (2005, 44), Gorin-Rosen (2010A, 230) and Pollak (2007, 126) and cylindrical and square sectioned bottles from Ramla, Sepphoris and Ha-Bonim (Pollak 2007, 127). These can be matched to examples from Nishapur (Kröger 1995, 88, 132, 149) and Samarra (Lamm 1928, 24, 79, 82). Nishapur Colourless versions of these forms have been identified from this study, for example miniature bottles from Sepphoris (SEP 3791-14, Fig 9.3d, Gorin-Rosen 2010C), Ramla (RAM 6297-07, Winter 2013; RAM 5947-29, Fig 9.3c, Gorin-Rosen 2011) and Ha-Bonim (HB 3032-09, Katsnelson Forthcoming A) and cylindrical and square sectioned bottles from Ramla (RAM 3592-06, Fig 9.3a, Gorin-Rosen pers. comms.; RAM 6490-11, Winter 2011). The stylistic parallels combined with compositional similarity, suggests that rather than the raw glass being traded, it was the finished glass objects themselves.

Compositional and stylistic matches are also seen from other sites. One of the Serçe Limanı vessels (Brill 2009, 481), a cut glass bottle, and several vessels from Fustat were made of a Nishapur Colourless type glass (Brill 1995, 213-4), while stylistic parallels between vessels from Fustat and those from Nishapur are observed by Kröger (1995, 9). Kato's Group PA-2 from Raya (Kato et al 2010A), a collection of 40 vessels, were

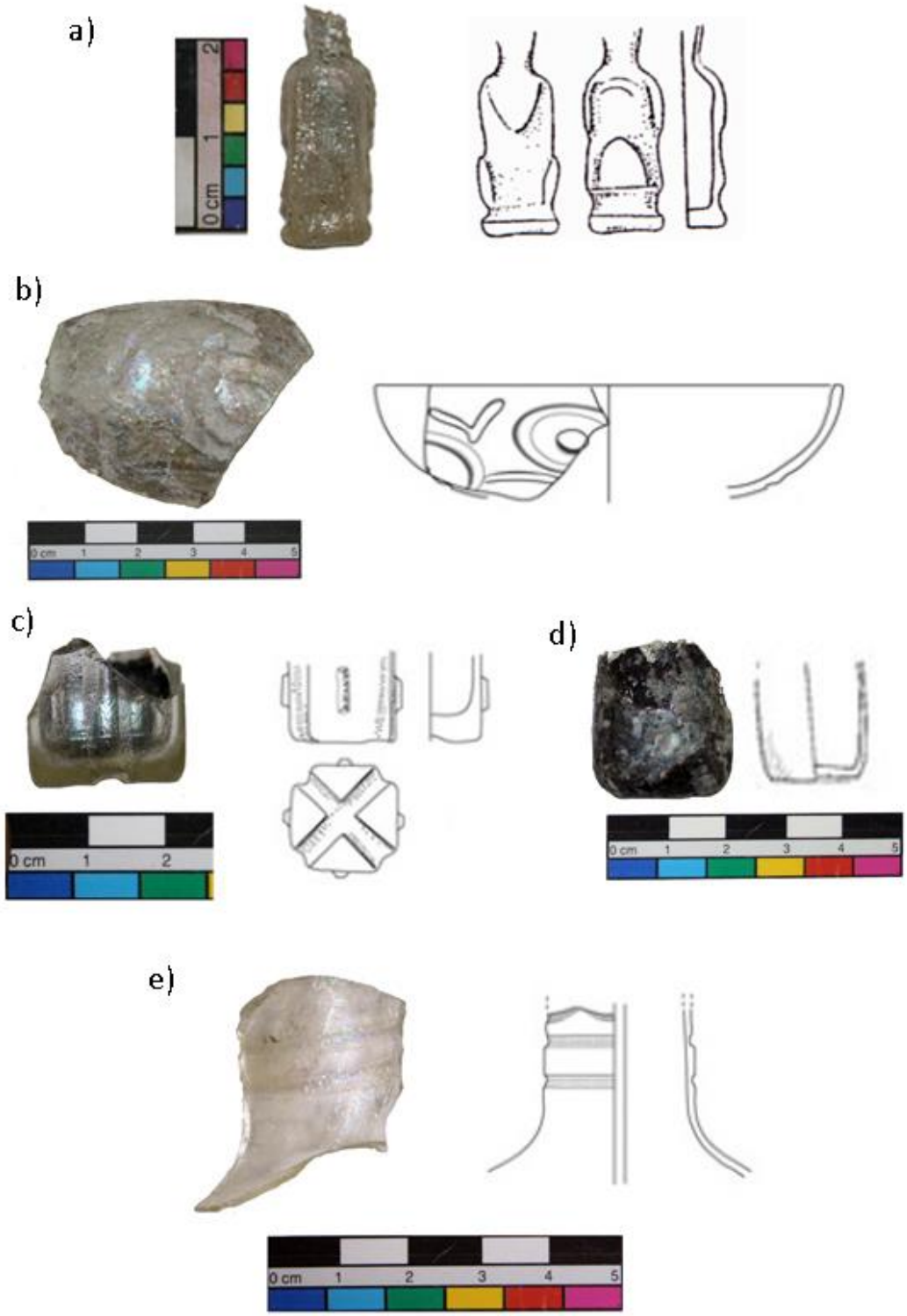


Fig 9.3. Vessel examples from group P-3, the Nishapur Colourless glass. a) RAM 3592-06 – miniature bottle; b) RAM 4768-10 – bowl engraved with geometric designs; c) RAM 5947-29 – square, wheel-cut bottle; d) SEP 3791-14 – small cylindrical bottle; e) RAM 5947-31 – bottle with grooved pattern.

also identified as a Nishapur Colourless type (Figure 8.2c). This group had a large proportion of wheel-cut decorated vessels described as Sasanian or post-Sasanian designs which led Kato et al 2010A, 1391) to believe these glasses originated in Mesopotamia.

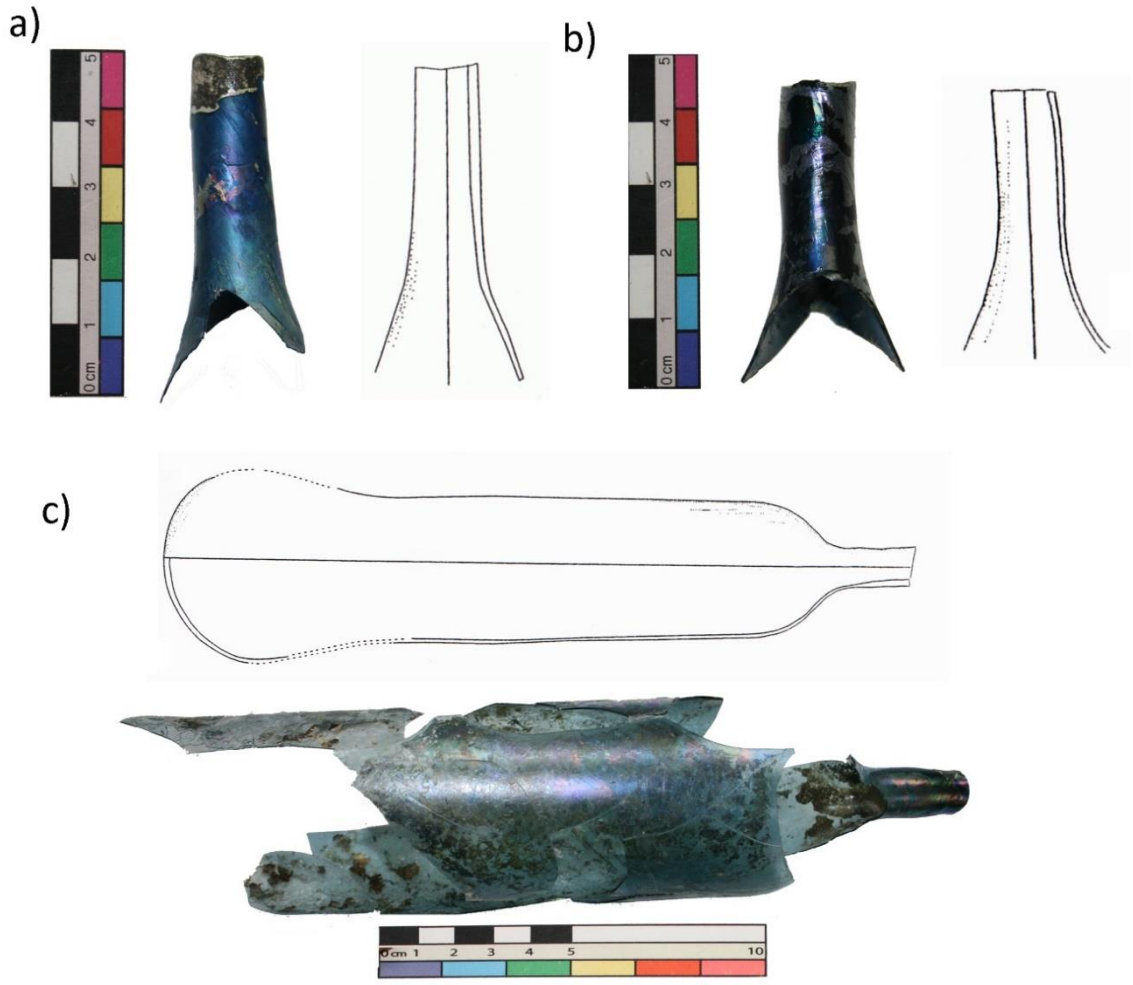


Figure 9.4. Examples of P-4, the Nishapur Coloured group. All vessels are elongated bottles: a) RAM 3847-05; b) RAM 6490-07; c) CEA W2S3-04

The trade of glass vessels from Mesopotamia to Palestine is most likely be have been overland, possibly along the roads of the Euphrates valley which formed part of a known trading network (Binggeli 2012). There was also the Great Post Road linking Baghdad via Raqqa and Damascus to Tiberias and Ramla. This road then continued on

to Fustat (Walmsley 2000, 299-300). Transport to Raya and Fustat might also have taken a route down the Euphrates, south along the coast to the Red Sea. It must be further noted that the P-3 vessels are mainly bottles, and it is likely that these were filled with a commodity which would have added to their value as tradable goods.

The P-4 group are cobalt blue glass of a Nishapur Coloured (Brill 1995) type. However, they are also a specific form of elongated bottle (Figure 9.4 a-c), described by Kröger as a mass produced, thin-walled, *'carelessly'* fashioned bottle, which is present in large amounts in Iran and Iraq. The bottles are thought to have been manufactured at various locations in the East (Kröger 1995, 74). Examples have been found at Nishapur, Ctesiphon, Samarra (ibid, 74-75), but also at various sites in Palestine: Ramla (Gorin-Rosen 2010A, 227); Caesarea (Pollak 2003, 228, 167) and also Egypt, at Fustat (Kawatoko and Shindo 2010, P1. 9. G-16) and Raya (Kato et al 2010A, Figure 2t). The Nishapur Coloured composition supports their proposed production in the East and suggests that they were traded as bottles to the Eastern Mediterranean. The large compositional range and variation in the composition evident within the cobalt additive (Chapter 7) suggests production at a number of different localities rather than a single production site. As with the P-3 glass, they were probably traded for their contents, which would add to their value, although, their contents are not known.

The bottles of Nishapur-type glass appear to be concentrated in the larger cities. P-3 was mainly found in Ramla, but single samples were identified from Tiberias, Sepphoris and Jerusalem. These were all larger cities, undoubtedly with areas of wealthier population and connected to a larger number of long distance trade routes. Ramla, in particular, was an important administrative and trading centre. The P-4 group had a slightly larger spread of vessels but was also mainly found in Ramla (7 samples), with single samples noted from Jerusalem, Tiberias and Caesarea, but also the military site Ashdod-Yam.

A number of high quality vessels are also identified of Tyre type glass (P-1) and were also possibly traded as vessels. Examples include an engraved, bevelled hexagon shaped bottle (RAM 4768-04; Gorin-Rosen 2010B); a unique horn-like object with wheel cut decoration (RAM 4768-06; ibid; Fig 9.5b); and a bottle with engraved star of David on the base (RAM 3897-08; Fig 9.5a; Katsnelson 2016). All are clear, colourless

glass and the decorations are of high quality. Several examples of different decorative types are also present: a wheel-cut engraved bottle (CEA 6194-11; Fig 9.6a) and beaker (TIB 5583-16; Fig 9.6b); a mould blown vessels six-sided bottle (CEA 6194-07; Fig 9.6c) and bottle/bowl with radiating ribs (HB 3032-18; Fig 9.6d); and vessels of Serçe Limanı forms, such as colourless cylindrical beakers (RAM 3847-07; TIB 5583-25; Fig 9.6e & f; Katsnelson 2016; Gorin-Rosen pers. comms.). While a large amount of chunk glass was traded into Palestine for use in local production, there may have been a trade in more specific or highly decorated items. These could have been made in Tyre itself. Al-Muqaddasi, writing around 985 CE reports Tyre as a glass-working centre specialising in wheel-cut glass (Carboni et al 2003, 140 & 147-8), although workshops at Tyre have

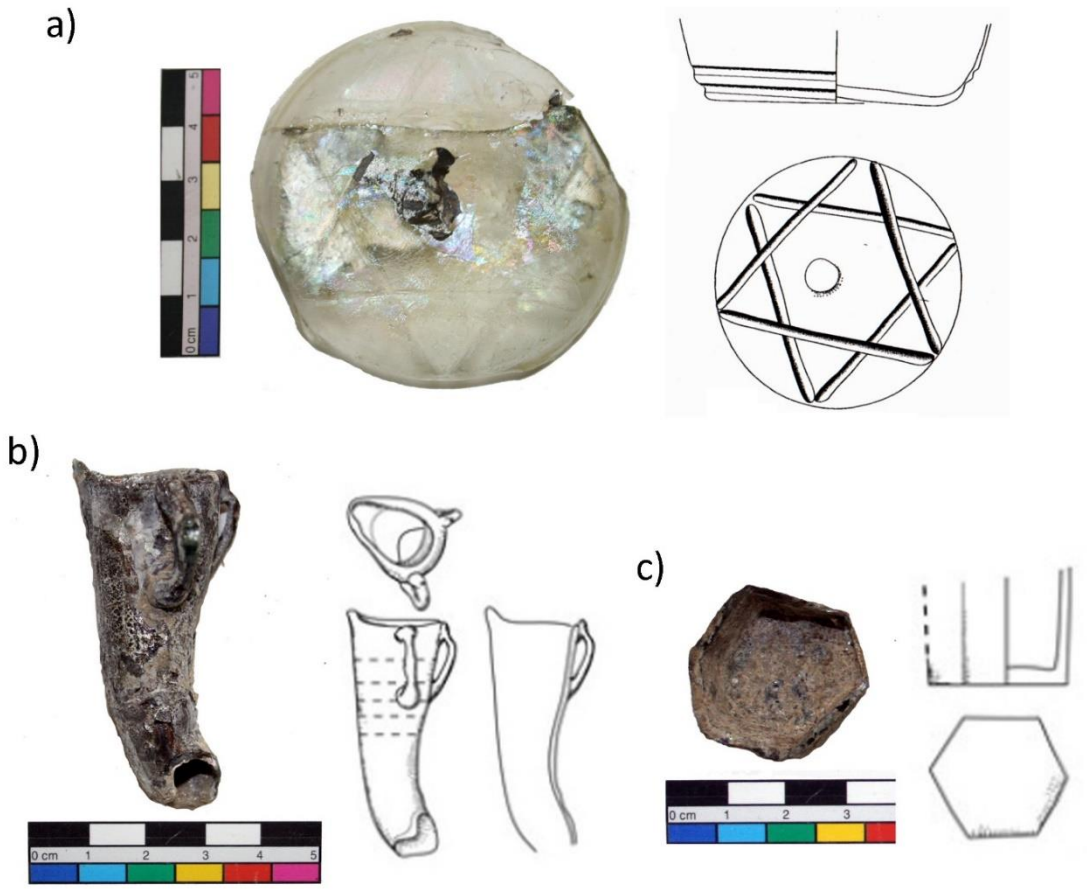


Figure 9.5. Examples of higher status cut glass vessels of Tyre type glass: a) RAM 3897-08, b) RAM 4768-06; c) RAM 4768-08

not yet been found. It is also possible that these glasses were worked elsewhere – both Damascus or Aleppo have been suggested as glass-making centres in the Ayyubid period (12th century; Henderson 2013, 267) but may have been operating earlier. The vessels could also have been worked at unidentified glassmaking centres in Palestine.

9.5.3 Evidence for Regional Specialisation

Over the years glass specialists have allocated the origins of particular techniques to certain regions and time periods and have suggested regional specialisms in some glass working forms, styles and decorations. In Early Islamic Egypt and Syro-Palestine pinched, impressed (tonged), applied and mould blown forms are recognised as being the most frequent (Brosh 2003, 339; Carboni 2001, 16, 163, 261). Wheel-cut decorations, including facet and relief-cut are common in the 9th-11th century. These techniques are usually associated with Sasanian traditions and production originating in Mesopotamian, with wheel-cut vessels frequently found at sites such as at Nishapur (Kröger 1995) and Samarra (Lamm 1928), but also Fatimid period Egypt (Carboni 2001, 73). Tyre has also been highlighted as probable glass cutting centres. Scanlon and Pinder-Wilson (2001, 11) comment that relief cutting was especially important in Fustat, although noting that wheel-cut patterns of Egyptian and Mesopotamian origins cannot be distinguished. Brosh also reports on the striking resemblance in wheel-cut decorated forms between Syro-Palestine, Mesopotamia and Egypt (Brosh 2003, 361). These similarities between regions highlights some of the inherent difficulties in provenance studies using style alone. Scratch decorated (incised) techniques have been suggested to Egypt and Syria (Brosh 2003, 361), although Carboni (2001, 76) alternatively suggests possible production in Mesopotamia. For cobalt blue scratch decorated vessels Scanlon and Pinder-Wilson (2001, 10) have proposed production in Egypt. For Luster painted vessels, dated from the 6th-12th century, production is suggested to Egypt and Syria (Carboni 2001, 52), while enamelled and gilded types after the 12-15th century are proposed to Syria (Raqqa, Aleppo, Damascus) and later in Egypt (Cairo).

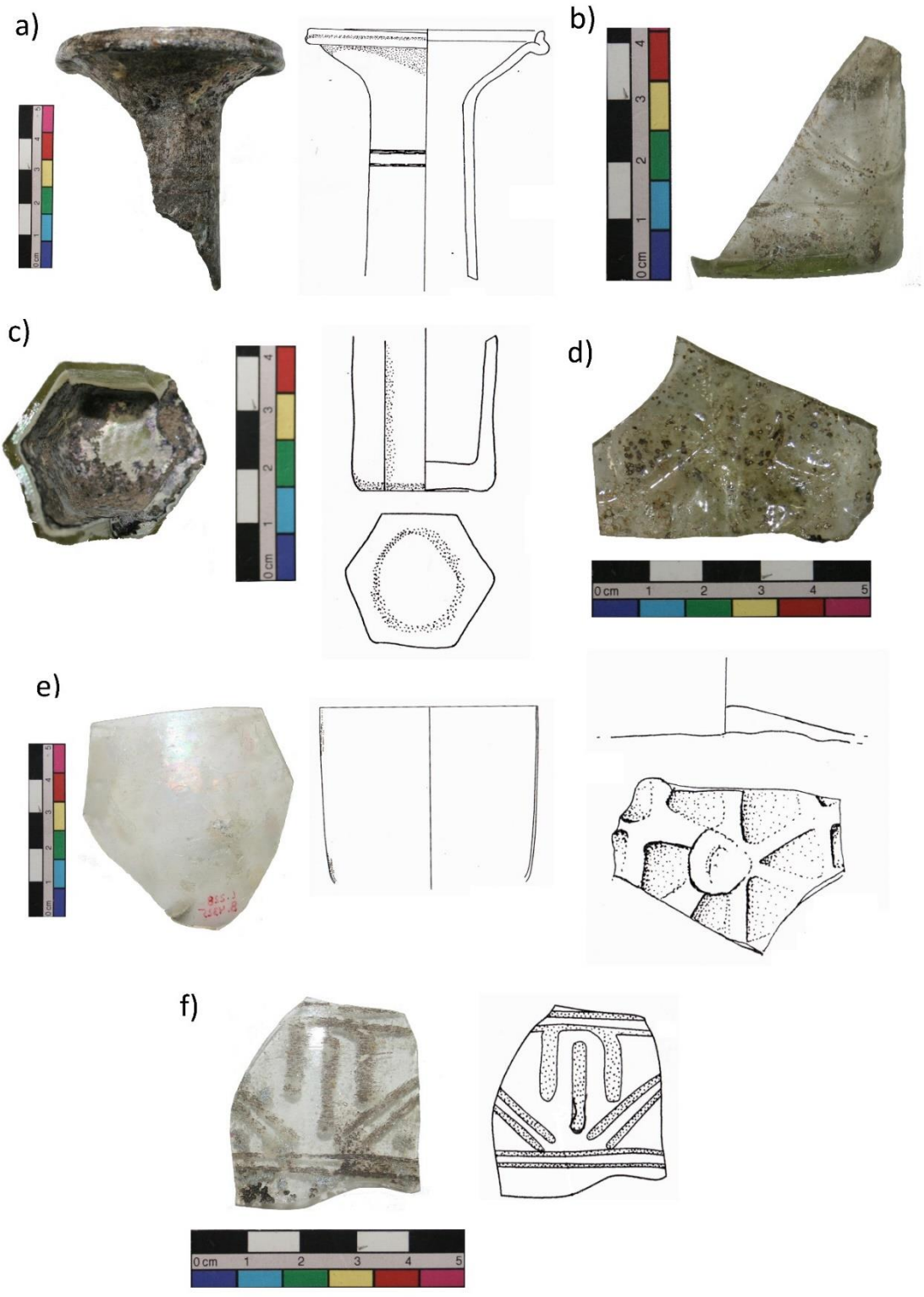


Figure 9.6. Examples of wheel cut glass of Tyre type; a) CEA 6194-11; b) TIB 5583-16. Mould blown; c) CEA 6194-07 and d) HB 3032-18. Serçe Limanı types; e) RAM 3847-07 and f) TIB 5583-29.

There is much uncertainty in the provenance of objects, often due to the similarities in techniques, decoration and forms between regions, and therefore, in specific circumstances, provenance can be facilitated by compositional analysis. Henderson et al (2016, 142) suggested that Mesopotamia was a regional specialist in wheel-cut techniques. The present results support the view that wheel-cut and certain categories of mould blown vessel were a product of Mesopotamia. However, it was not the only producer as wheel-cut examples in local Tyre fabric are also identified from the Levant.

Mesopotamia is a regional specialist in the elongated bottle, as indicated by the P-4 group. It is also noted here that all the vessels of *'Serçe Limanı'* types, i.e., those types which are identified from the Serçe Limanı shipwreck, such as cylindrical beakers (Figure 9.6 e &f) and large plates (RAM 6297-09 – 11; Winter 2013), have Tyre type compositions. This demonstrates a link between local fabrics and certain regional forms and styles.

Two scratch decorated vessels and a shoe-shaped object of Abbasid date (RAM-3592-03; RAM 6297-06; RAM 5583-06) are cobalt blue using an Egypt II type glass. Brill (1999A & B) also analysed a number of scratch decorated objects from various sites, including from Fustat, and they have compositions which is also similar to Egypt II glass, as discussed in Chapter 7. Excavations in Fustat uncovered other scratch decorated cobalt blue fragments (Scanlon and Pinder-Wilson 2001, 82) and in addition, a co-blue shoe-shaped object (ibid, 63). These objects closely parallel the three vessels identified in this study in their form and decorative technique, potentially suggesting they were traded as vessels to Palestine, rather than raw glass. It is also evidence for a regional specialism in scratch decorative techniques operating in Egypt.

9.5.4 Smaller Compositional Types and the Evidence for Non-Centralised Production

Several smaller compositional types of plant ash glass were identified which might represent smaller scale regional production. The P-2a and b groups potentially belong in this category. They are small groups, mainly of low value domestic forms. P-2a dates to the late 8th to possibly the 13th century and was found from a number of

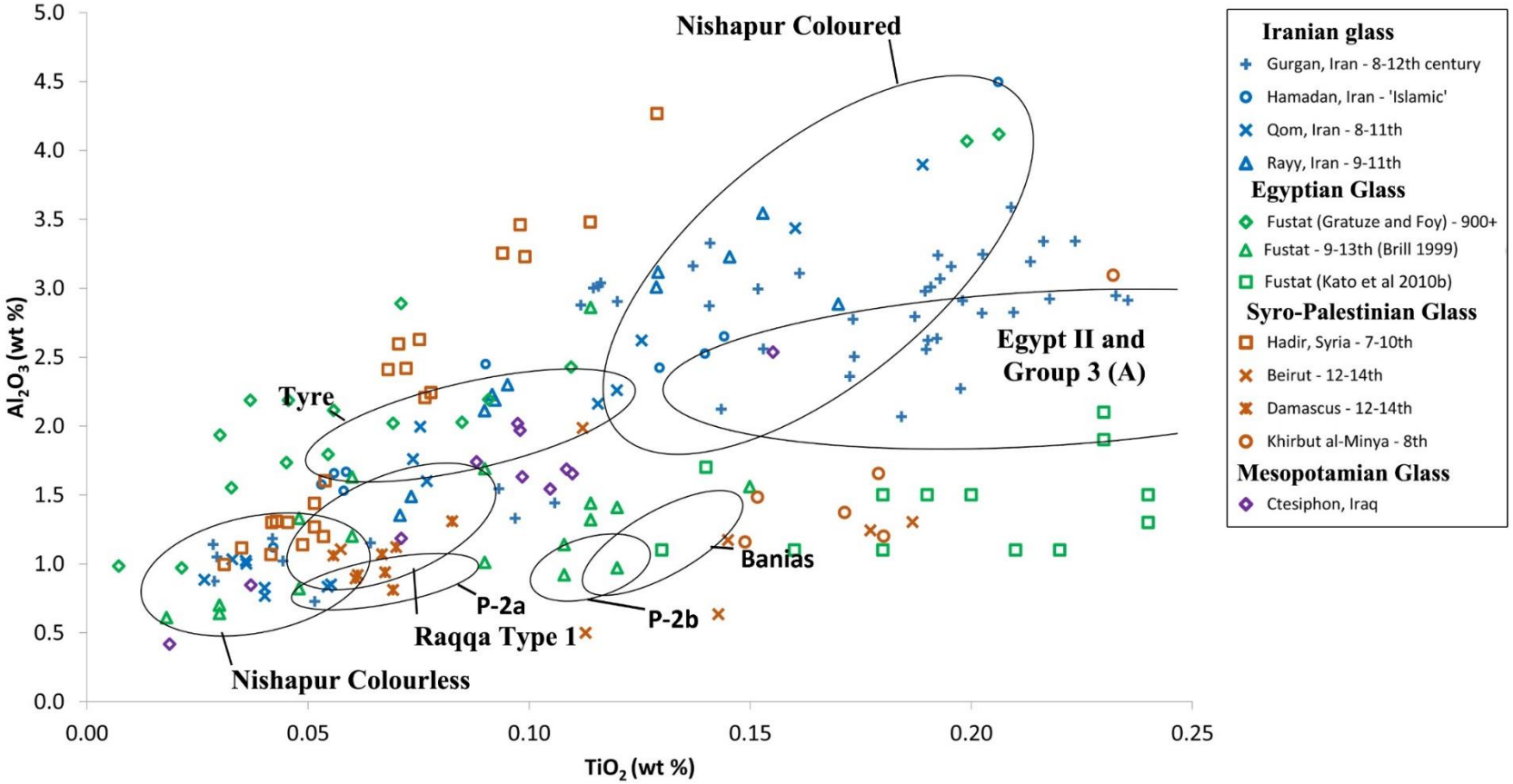


Figure 9.7. Data taken from various consumption sites from Syria, Palestine, Iran, Mesopotamia and Egypt. The data sources are as Figure 9.2, but with the data from Raya, Wadi al-Tur and Serçe Limanı being removed due to lower data quality. The circled fields are defined from the data presented in Figure 7.6a and 7.13, Chapter 7.

sites in Palestine, while P-2b dated only to the 11th-13th century and came from Bet Shean. Both are likely of Syrian production, and might represent localised production types, the P-2b group, being found at only one site, might suggest production from the locality of Bet Shean, however, the lack of additional analyses from this time period may mask a more ubiquitous production group. These two small production types, when taken alongside Raqqa Type 1 and Type 2 already noted, suggest that at least four production types were being manufactured in Syria between the late 8th to around the 12th century. In figures 9.2a and 9.7 a range of Syro-Palestine glass from Damascus and Beirut dating to the 12th-14th century, 7th-10th century Hadir, Syria and 8th century Khirbut al-Minya, Israel are presented. The glass from all four sites demonstrated overlaps with Raqqa Type 1 and the P-2a and b groups, and less so with material from Tyre. The site of Hadir also indicated quantities of glass with Mesopotamian glass signatures. However, from Beirut and Khirbut al-Minya unidentified glass types with higher titania and lower alumina (Figure 9.7) are observed, and these might suggest yet another production type occurring in the region.

It suggests the existence of a number of production sites within Syria, although spread over a number of centuries. It could be that different urban centres developed their own primary glass production within extramural industrial areas as suggested by Henderson et al (2016, 142), and as seen at Raqqa. Is this evidence for a dispersed production model that began to operate with plant ash glass? The definition of dispersed production, as suggested by Freestone et al (2002A), is that of a wide spread of workshops making their own glass from the raw materials and then shaping and selling the vessels. An alternative model is a more localised form of centralised production. For example, if each urban site had their own primary production and the raw glass was traded to workshops within the city and the surrounding region, to be shaped at secondary sites. The evidence from Raqqa suggest that primary production and secondary working was occurring at the same locality, but the scale of production might also imply trade of raw glass which is yet to be identified. Raqqa also had a number of compositional types, suggesting that at least some raw glass was being imported to Raqqa, although imported material seems of less consequence in 11th

century Tel Fukhkhar as compared to earlier glass working at late 8th-early 9th century Tel Zujaj. At current, the compositional and archaeological evidence to be able to distinguish between dispersed and more localised version of centralised production is lacking within Syria. Furthermore, the wide timespan of the analysed samples may present a succession of glass working centres changing over time rather than concurrent production at a number of sites. With better dating and more samples it will be possible to construct a clearer understanding of production in Syria.

In addition to the types found in Syria, three potential additional production types are also suggested by the outlier samples: an unknown Syro-Palestine type (CEA 6194-01), a potential Egyptian type (CEA 6194-05) and a high alumina Mesopotamian type (AY 2989-08). These imply a greater production variety than seen in the natron glass, and might indicate the opening up of primary production to a wider range of practitioners which might have been due to easier access to flux raw materials. Alternatively, a broader range of identified types might, in part, be due to an increase in long-distance transportation of glass during the Abbasid period through trade networks linking up a larger number of production sites over a wider region. Nonetheless, looking to Figure 9.7, the wide spread of values highlights the fact that not all the production groups are accounted for, and it is likely that many more primary production centres, especially of Syrian and Egyptian origin, were operating and are yet to be recognised.

9.5.5 Changes in the Supply of Glass in Palestine: Umayyad to Abbasid-Fatimid Periods

In Figure 9.8 the origins of the vessels are presented split into two chronological periods – Late Byzantine-Umayyad covering the 7th to mid-8th century – and the Abbasid-Fatimid period, covering the mid-8th to mid-11th century. This image illustrates that the location of glass production and supply changed between the two periods. The 7th-mid 8th century was dominated by Levantine glass from Palestine and large amounts of Egyptian glass appearing from the early 8th century. In the Abbasid period this picture shifts, Levantine production disappears, Egyptian glass continues into the 9th century although at a reduced level, but the overwhelming majority of glass in the

Abbasid-Fatimid period is supplied from Tyre. Tyre is relatively close, 90km north of Caesarea and relatively accessible to Palestine. Primary production is no longer present in Palestine, and this would have most probably caused some economic harm, nonetheless, smaller glass workshops continued to fashion glass for local use.

What was distinctly new in this period was the import of vessels from Mesopotamia (groups P-3 and P-4), cobalt blue decorated types from Egypt (N-3 Co) and possibly decorated types from Tyre (P-1). The appearance of Mesopotamian glass is an indication that there was an increase in East-West trade that appears to accompany the Abbasid revolution in 749 CE, and this ties in with the shift of power eastwards to Baghdad upon its founding in 762 CE. This period was also accompanied by the appearance of new Eastern styles of glass (Brosh 2003, 324) and new glass decorative techniques (Carboni 2001, 16), as well as the appearance of Mesopotamian pottery types, such as Iraqi fine and polychrome glazed wares (Wickham 2004, 168). Examples of Mesopotamian ceramic have been found from Ramla, and include turquoise and

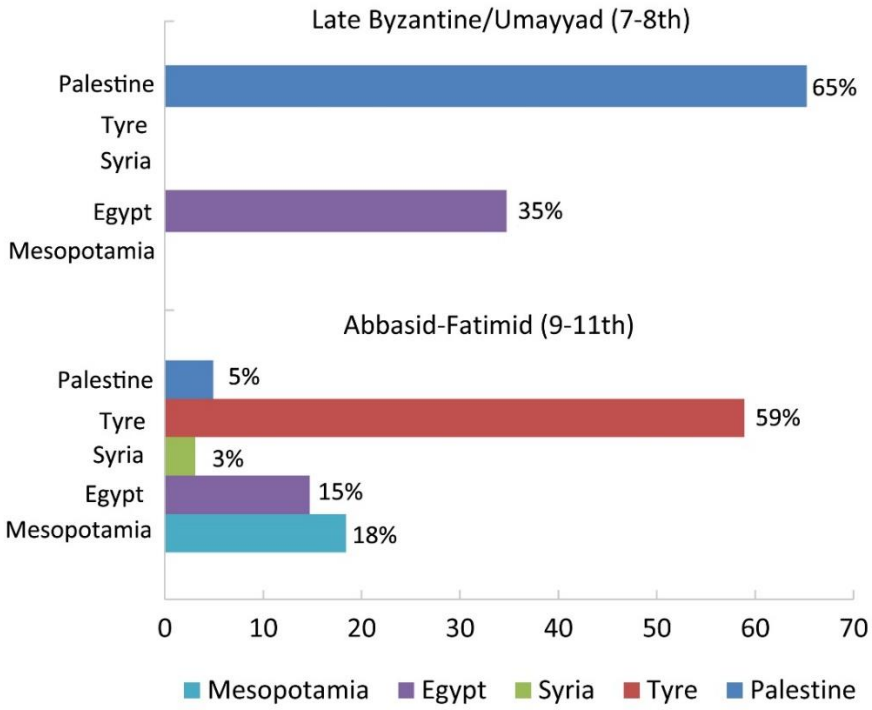


Figure 9.8. Percentage frequency of vessel grouped by origin and sorted by chronology to the Late Byzantine-Umayyad (7th-mid 8th) and Abbasid-Fatimid period (9th-11th century).

white glazed wares (Cytryn-Silverman 2010, 109, 112). The Umayyad-Abbasid transition appears, therefore, to indicate a change from localised distribution of Levantine raw glass in Palestine and the import of raw glass from Egypt, to long distance trade in vessels from Mesopotamia and possibly cobalt blue examples from Egypt, and raw glass principally from Tyre. This pattern seems to coincide with the fundamental shift in the economy of the Caliphate at this juncture.

Eighth century Palestine was relatively prosperous. This prosperity was driven by large towns, good road networks, and a ruling elite that encouraged mercantile activities (Walmsley 2000, 304), and this facilitated the development of a strong local craft industry, including glass vessel production. Walmsley has observed that during the Umayyad period most of the ceramic forms in the region of Palestine were local types, tending to be traded up to 50-100km from their production source (Walmsley 2012). Imported types are recognised as being few and much less frequent than in Roman and Byzantine periods. Walmsley comments that demand for household pottery was *'almost solely satisfied by local production'* (Walmsley 2000, 322). He suggests that the reliance on local distribution was down to the fiscal separation between different regions of the caliphate (ibid 343), i.e. taxation revenue tended to be redistributed within the regions and not sent to the capital. Local craft industries themselves were bolstered by frequent markets and populous towns. Distribution networks for goods have been mapped using roads and known trade fayres, indicating Palestine and Syria to be linked by two overlapping trade zones during the 8th century that connected the major cities (Bengali 2012).

The system of localised procurement and distribution changed in the late 8th-early 9th century. The Muslim elites lost their entitlement to the *'ata*, a stipend each Muslim citizen received out of regional taxation, and instead this income went to the state (Walmsley 2000, 272; Wickham 2004, 168). This ended the fiscal independence of the provinces and resulted in taxation concentrating in the centre, greatly increasing centralisation of the Abbasid state, and this, as commented by Walmsley *'resulted in a substantial reorientation of trading systems'* (Walmsley 2000, 343). It led to increased demands for consumer goods, stimulating a growth in long distance trade as the movement of goods to and from provinces increased. This change is evidenced by the

appearance of Mesopotamian vessel types in Palestine and the transfer of vessels and their contents long distances from Egypt, Mesopotamia and Tyre, as well as the continued trade of raw glass.

One aspect of the changes in glass supply after the 10th century is the absence of Egyptian plant ash types identified in Palestine. In the 9th century Egypt became more autonomous and economically prosperous under the Tulunids (868-906), Ikhshidid (935-969) and finally, the Fatimid caliphate (969 onwards). It resulted in increased trade ties between Palestine and Egypt due to shared rule (Schick 1998, 78), as well as a more general shift in trade westwards to the Mediterranean and North Africa (Wickham 2004, 173). However, these increased ties are not evident in the glass of the 10th century. There are several possibilities why this is the case; that Egyptian glass has not been accurately identified; that Egyptian glass production collapsed in the mid-late 9th century and plant ash types were slow or unable be to developed; or that Egyptian glass was not being imported into Palestine. Some Egyptian plant ash types have been identified. They include the late 9th-10th century Group 3A identified from glass weights from Fustat (Gratuze and Barrandon 1990; Chapter 4). Glass from Fustat in Figure 9.7 demonstrate are least two unidentified glass types: a low alumina, high titania group and another with high alumina, low titania. Furthermore, glass from Banias, dated to the 11th-13th century (Freestone pers. comms.) has a trace element signature somewhat similar to other Egyptian glass types, potentially suggesting an Egyptian origin. This glass falls into the region of Figure 9.7 occupied by some of the Fustat samples. These types potentially represent Egyptian production. It suggests that the lack of Egyptian glass in 10th century Palestine is possibly influenced by the strength of output at Tyre, Syria and Mesopotamia, rather than a lack of Egyptian production. The development of plant ash glass in Egypt does not seem have been held back by the later adoption of plant ash glass.

9.5.6 Conclusions on the Organisation Changes in Glass Production

The Abbasid glass industry as seen from Palestine was more complex in comparison to the Umayyad industry. It is recognised here that the plant ash industry

had several primary production centres operating. Tyre type glass represents centralised production and was in operation during the late 8th to at least the 11th century and formed the main pool of glass in use in Palestinian glass workshops. There was also a trade in superior quality vessels that began in the Abbasid period, with vessels coming from Mesopotamia, Tyre and possibly Egypt.

The identification of a number of smaller production types from this study and other sources suggests the emergence of a number of small scale production sites operating within Syria from the Abbasid period onwards. However, the nature of this production, and whether it indicates a shift to a dispersed production model or a localised form of centralised production cannot yet be identified. These types possible represent sub-groups within regions, and possibly originate at urban sites (Henderson et al 2016). The Nishapur Coloured Group, as represented by the P-4, also shows indications that a more dispersed pattern of primary production might be in operation within Mesopotamia and Iran. The evidence for this in the P-3 group is much less so, with the homogeneity within this group suggesting a single production site.

These results indicate a much more variable and complex picture of glass supply. Raw glass was traded to fulfil the needs for domestic supply, while higher status vessels were transacted longer distances. The distribution of glass is also related to the potential transport of commodities within the vessels, and the trade of vessels between regions of different decorative specialisms.

Chapter 10

Final Conclusions and Further Work

10.1 Summary and Conclusions

Almost 300 well-contextualised glass vessels were analysed as part of this thesis. The samples were taken from 19 excavated consumption sites at 11 localities across Israel and encompass an approximate 500-year period. Four natron glass groups and 4 plant ash glass groups were identified, plus a small quantity of outlier types. These compositional types could generally be associated to known production sites or regions, and using this data alongside chronological and contextual information enabled the identification of a series of developments in the glass industry that occurred in the centuries after the Arab conquest. Such developments include diachronic changes in the glass supply of Islamic Palestine and developments in the centres of production. Understanding these changes has facilitated a much more complete comprehension of the causes and chronology of the change from natron to plant ash glass technology. This project has also demonstrated the utility of accurate, high precision techniques with low detection limits for the recognition of compositional groups, identification of vessel provenance, and also for the investigation of colourants and recycling within samples. It must also be noted that the conclusions of this thesis could not have been drawn without such well-contextualised samples, and that the combination of the analytical technique with suitable samples enabled a greater scope for interpretation.

The natron glass was matched to known groups, identifying two Levantine types (N-1/Apollonia-type/Levantine I and N-2/Bet Eli'ezer/Levantine II) and two Egyptian types (N-4/Egypt I and N-3/Egypt II). These groups were characterised using their trace elements for the first time. Separation of the Levantine natron glass types was

principally accomplished with the major oxides – soda, silica, lime and alumina – using a ratio-ratio bivariate plot (see also Al-Bashaireh et al 2016). It was found that trace elements are not suitable separators between the two Levantine groups, although strong differences and distinctive trace element profiles were displayed between the Egyptian glass types. Furthermore, it was demonstrated that vessels from Apollonia and Jalame could be distinguished compositionally. As both these production sites are included inside the definition of Levantine I (Freestone et al 2000), the designation 'Apollonia-type' was used throughout this thesis as this term more accurately describes the composition of the N-1 group. Similarly, Bet Eli'ezer was used for N-2 rather than Levantine II. It is recommended that future researchers also try to link vessels to production types rather than the larger umbrella term Levantine I where possible, as this might more accurately identify the origin of their samples. Furthermore, the abandonment of the Levantine I and II terms may aid the identification of new production types and locations, and facilitate a better understanding of the glass industry in this region.

This project recognised and defined regional plant ash compositional groups through the reinterpretation of data from literature sources, as well as from unpublished data and also reanalyses of previously published samples. This was combined with new analyses from samples in this study, which generated a large body of data, including the characterisation of a number of plant ash groups from Palestine, Syria and Mesopotamia using trace elements, which adds to the trace elemental data recently published by Henderson et al (2016) of mainly later Islamic glass and that of Mirti et al (2008; 2009) of Sasanian glass. In particular, this study was able to fully characterise glass of a Tyre-type (P-1) and produce more analyses of Nishapur Coloured (P-4) and Colourless (P-3) Types, and identify new plant ash glass types of possibly Syrian origin (P-2 a & b).

One of the main contributions of this project is in developing the understanding of plant ash glass by the recognition of three principal flux types: Eastern Mediterranean, Mesopotamian Type 1 and Mesopotamian Type 2. These groups expand on the two Sasanian types identified by Mirti et al (2008; 2009), the two Nishapur types identified by Brill (1995), and the distinction between Syrian Islamic and Sasanian glass identified

by Freestone (2006). The groups are distinguishable using their flux oxide ratios (MgO/CaO and K_2O/P_2O_5), and can be further aided by the use of Al_2O_3. These oxides have proven to be useful separators between the main regional compositional types. Close similarities between Sasanian and Islamic Mesopotamian production have also been demonstrated, which build on the links between glass from Nishapur and Samarra and that of Sasanian production as proposed by Wypyski (2015). This project suggests, as per Wypyski (2015), that the Nishapur Colourless glass type, which is found in quantities in Palestine, Raya (Kato et al 2010A), Fustat (Brill 1999) and Serçe Limanı (Brill 2009), was more likely produced in Mesopotamia, rather than Nishapur, as suggested by Kröger (1995) and Henderson et al (2016).

The separation of plant ash glass groups based upon the elemental contributions of their silica sources is in some cases difficult due to compositional overlaps, this appears particularly apparent in the separation of glass groups which use silica sources of high purity – such as Raqqa Type 1, Nishapur Colourless, Sasanian 2, Banias, P-2 (a & b). While separation can be made from the Mesopotamian glass using the flux elements, the same cannot be said for the other groups. In these circumstances the use of trace elements and REE can be valuable discriminators, if only to rule out a match. For example, in REE the glass from Banias was shown to differ from other Syrian glass types, indicating a separate origin, while P-2 (a & b) were found to closely match Raqqa Type 1 in trace and REE, suggesting a potentially Syrian origin.

Separation between production groups was found to be most effectively accomplished using Al_2O_3, TiO_2 and ZrO_2 with supporting information from REE profiles and the Eu anomaly. Some groups were easily identifiable as production types (e.g. Tyre glass), however, other groups displayed a larger compositional range and more diffuse spread of compositions. For example, it is likely that the broad compositional spread of the Nishapur Coloured group (P-4 group) possibly implies more than one production site, pointing to this group being more likely a regional compositional type. Furthermore, a number of Syrian plant ash types were noted in this project, such as those from Raqqa (Henderson et al 2004) and which are noted from other sites in Syria (Henderson et al 2016). Henderson suggests these as regional sub-types, and a proliferation of samples with finely defined compositions may pose problems for future research, especially in

the investigation of the possibility of dispersed primary production in which a larger number of glass workshops using similar raw materials might be active. Additional distinction may be possible using isotopes. For example, Ganio et al (2013) was able to recognise isotopic variation within the Sasanian groups identified by Mirti et al (2008; 2009), suggesting that more than one production site was operating but producing products indistinguishable in composition. Isotopic variation in strontium is noted for Syria (Henderson et al 2009), and might, in some cases, be useful in the identification of separate production types if overlap is shown.

Furthermore, it is noted that in areas where the regional geology is generally homogenous, use of trace elements, particularly the REE, is not helpful in defining productions. For example, all the Levantine glass of natron and plant ash types – Apollonia, Bet Eli'ezer, Tyre – have strikingly similar trace element profiles in their silica source related elements and are only distinguishable using major and minor elements, principally within the principal sand minerals, such as feldspar or calcite/shell.

This study also proposed a method for the identification of background levels of colourant elements by using a selection of colourant elements and comparing concentration against vessel frequency. This enabled the estimation of the quantities of fresh glass and of glass containing recycled material. This is useful, as the identification of fresh glass can indicate if production was still occurring during a given period. It also gives an idea of the quantities of fresh glass coming into circulation, providing an indication of glass output and the general vitality of the economy. This investigation was also able to show that total colourant content correlated with P_2O_5, demonstrating the increase of both in recycled glass, with the highest correlation seen in glass with total colourant contents <200ppm. No contamination was noted from oxides from the furnace lining. This investigation builds on work recently completed by Jackson and Paynter (2016).

The investigation of the cobalt blue samples suggested that three types of cobalt additive were in use, one for each of the three base glasses (N-3 Co-blue (Egypt II), P-1 Co-blue (Tyre-type) and P-4 (Nishapur Coloured). A fourth type, high in zinc, was

recognised from one of the literature groups (Brill's (1999B) Scratch Decorated Glass/Egypt II). The three cobalt additives for this study's samples were similar, each containing elevated quantities of iron, copper and manganese, with other elements being group specific, such as zinc and nickel. These elements suggested a closest match to the cobalt-manganese mineral asbolane, which is often associated with deposits of other minerals, such as copper, iron, zinc and can also contain nickel. This mineral can be found at Qamser near Kashan, Iran (Abe et al 2012; Kaczmarczyk 1986; Kaczmarczyk and Hedges 1983), and this currently suggests a potential location for the cobalt additives used in the glasses analysed here, although further confirmation is not possible at this time. Similarly, the manganese oxide additives in the plant ash glass could be distinguished between glass groups based on manganese oxide/barium oxide ratio, suggesting the source was different for each production type. The mineral additive is suggested as a pyrolusite mineral containing smaller quantities of psilomelane.

This thesis has been able to contribute answers to many of the major questions and aims outlined in Chapter 1. The results suggest that in the decades following the Arab conquest of Palestine very little change in glass production was initially observed, with glass supply continuing to follow Byzantine practices in composition, organisation and production location. It was only during the early 8th century that major developments started to appear. These coincided with the important reforming reigns of al-Malik and al-Walid during the early 8th century, and continued with the start of the Abbasid Dynasty in the mid-8th century. The changes were three-fold: i) a shift in production from an Apollonian glass type (Levantine I) to the lower soda of Bet Eli'ezer glass (Levantine II); ii) the appearance of large quantities of Egypt II glass, and iii) the appearance of plant ash glass types in the late 8th century, which is so far the earliest identified Islamic period plant ash glass in the Eastern Mediterranean but matches the dating of samples in Raqqa (Henderson et al 2004). These changes in recipe and the appearance of non-local glass types are interpreted to suggest that that the Palestinian glass industry was suffering a decline during the 8th century. Changes in glass recipe imply that natron became less readily available, and this would have raised the price of glass through increased raw material costs, but also by additional fuel requirements.

The workability of the glass would have been reduced too. Thus, non-local, imported natron types from Egypt and plant ash types from Tyre and Syria began increasingly to supplant local production. The reductions in the natron content of Levantine glass persisted over an approximate 50-year period until production in Palestine eventually ceased at around the end of the 8th century, marking the end of over a thousand years of natron glass production. After this time only recycled types of Levantine natron glass are found. Around 100 years later, in the mid-late 9th century, natron glass production in Egypt also appears to stop (Gratuze and Barrandon 1990; Sayre and Smith 1974), and as seen here from the disappearance of Egypt II type glass in the 10th century.

The chronology of changes to production suggests a reduction in natron availability which intensified over a 100 year period, starting in Palestine in the 8th century and eventually spreading to Egypt in the 9th. This long-term and gradual trend, as well as the permanence of the cessation of natron manufacture in both regions, when combined with a downward trend in the soda content of glass recognised over an 800-year period, has suggested that a range of long-term and also short-term factors were in play which came to a critical juncture in the 9th century.

Detailed examination of the potential factors have ruled out political instability (civil war, raiding, invasion) disrupting trade and natron extraction, and also climatic effects, due to the speed, chronology, duration and permanence of the noted change. Instead, technological change has been attributed to a combination of economic factors which were intensified by cultural and political changes. Economic developments in the caliphate of the 8th and 9th centuries may have caused increasing demand for natron driven by an expanding economy and strong craft industry. Natron was a finite source, with extraction per year fixed by what the lakes were able to supply, with legacy extraction figures suggesting an upper limit of 1000-1600 tonnes per year. It was not only used for glassmaking but for a variety of personal and industrial uses. In particular, natron could be used as a raw material in both soap and textile production, both industries of which underwent a great deal of growth during the Islamic period, particularly the textile industry of the Tulunid and Fatimid periods, one of the largest industries in Egypt. Medical uses might have also been a factor. The political situation

of the Tulunid and Fatimid periods (9th century) may have further exacerbated the situation by the imposition of a state monopoly, trade tariffs and price increases on natron from this time until the Mamluk period (15th century).

The price of natron during the 8th and 9th century is not known, however, the cost during the 12th and 13th centuries is recorded in documentary sources at 70 and 300 dinars per qintar respectively. It was subsequently calculated that the cost of trona at these prices was 2/3 and over 3 times the price of the glass produced. This clearly demonstrates that the cost of natron was too high for its use in glass production. It can be implied that sometime during the late 9th century a line was crossed that made natron no longer cost effective in glass production. This line was crossed in Palestine earlier than Egypt probably due to the transport costs of shipping the natron from Egypt to Palestine.

Compared to this, the other industries may have had advantages over the glass trade; the price of the end-product, particularly textiles, was expensive and so they might have been able to afford higher prices for the natron, while glass was a more every-day product, whose price may not have been as readily able to increase. The individual batches of natron required for textile and soap production, or medical use, was also most likely smaller and so the financial outlay was reduced compared to that of glass makers who would have purchased very large quantities at a time. The larger requirements in glassmaking may have lead glassmakers to be more susceptible to price increases. Other industries, therefore, may have been able to outcompete the glass industry for the natron. The reduction in soda over the previous centuries suggests that earlier price increases may have been offset by reducing the soda content of the glass at the expense of additional fuel requirements, but an upper limit for this may have been reached in the 9th century.

Using aspects of the composition of plant ash glass and what is understood of the manufacturing processes, the origins of the plant ash glass technology in the Levant was examined. It was concluded that there is no evidence to suggest the technology was derived directly from Sasanian practices. Based upon mainly indirect evidence, it was instead suggested that an Eastern Mediterranean origin is more probable. This

took into account similar furnace sizes between Roman/Byzantine production sites and production at Tyre and similarities in the organisation of production; the routine use of manganese dioxide as a colourant in Islamic plant ash glass which follows on from Roman and early Byzantine glass making practices but is not seen in Sasanian glass production; and the occurrence of plant ash glass in Roman and Byzantine, suggesting that the use of plant ash in glass making was a known technology already in use for small scale production for specific glass types. Finally, a potential mechanism was proposed for how glass making became embedded at Tyre via the forced relocation of glassworkers during the reign of Caliph Hisham in the mid-8th century. The movement of glass workers from the glassmaking region of north Palestine would have transferred glassmaking knowledge northwards to Tyre. This was combined with the fact that suitable low-lime sands for the production of plant ash glass could be found at Tyre but were not available in Palestine, as demonstrated by the failure of the glass slab at Bet She'arim. The increasing price of natron and competition from other sources, coupled with the wrong sort of sand, ultimately caused the disappearance of glassmaking from Palestine.

The final set of major questions concern the organisation of production and whether the centralised model of Roman and Byzantine glass production continued during the Early Islamic period and into the era of plant ash glass production. The answering of this question involved a wide range of available data, including glass compositions, vessel typology to determine local production from imported types, data from the Serçe Limanı shipwreck and documentary evidence of the trade in glass from the Cairo Geniza. It is concluded that centralised production continued until at least the 12th century using glass produced from the primary production site of Tyre. This type formed the dominant composition in Palestine. The evidence suggests raw glass was not only traded from Tyre to Palestine, but also to Egypt and Turkey. There is also some compositional evidence to suggest a trade of Tyre glass to Raya.

A number of smaller glass types were also identified which may indicate a greater complexity in the supply of plant ash glass as compared to the natron glass industry. Henderson et al (2016) suggested a more dispersed model for production in Syria, possible centred around production at urban centres. The evidence for non-

centralised production is based upon a number of production types being found, for example three plant ash types are noted from Raqqa (Henderson et al 2004), two further types similar in composition to Syrian glass were identified in this study (P-2 a & b) and further identified types are recognised from Henderson et al's (2016) investigations of Syrian glass from a number of urban sites. However, whether this fits the model of dispersed primary production where individual workshops made their own raw glass which was then shaped into vessels and sold (Freestone et al 2002A) or a more localised form of centralised production in which each city had its own primary production and the raw glass was traded locally to workshops in the city and surrounding area, cannot be determined at this time. Nor is it known if raw glass was moved between the cities of Syria at all, unlike the clear evidence for the trade in raw glass from Tyre to Palestine, although the movement of raw glass from Syria is possibly implied by the utilitarian, low value, vessels found at Raya which are suggested as a Raqqa type glass (Kato et al 2010A). Furthermore, the utilitarian forms of the vessels made of P-2 (a & b) glass in Palestine also imply a trade in raw glass rather than finished vessels, as it seems unlikely that low value domestic vessels would have been traded long distances.

The trade of vessels from Mesopotamia marks a distinct shift in the glass supply of Palestine that appeared to coincide with the start of the Abbasid caliphate. This is evidenced by the appearance of vessels of Mesopotamian compositions of specific forms or decorative types. The shift in trade patterns appears to coincide with the transfer of the capital to Baghdad during the early Abbasid period, subsequent growth in interregional trade at this time was in part stimulated by changes to the taxation system in which revenue was directed from the regions and concentrated in Iraq (Walmsley 2000). Mesopotamian types found in Palestine include vessels made of Nishapur Colourless (N-3), a high quality clear glass, often with wheel-cut decoration, and elongated cobalt blue bottles with Nishapur Coloured base glass (P-4). As well as being found in Palestine, chiefly in Ramla, these compositions and vessel types are recognised from Fustat and Raya in Egypt, and also in the Serçe Limanı shipwreck. This indicates an East-West trade in vessels occurring in the 9^{th}-11^{th} centuries. No vessels of these compositions are seen in later periods, although this might not be representative

due to the fewer numbers of samples. Furthermore, high quality vessels of Tyre type glass are also found, and might suggest a local trade in specific vessels around the region. Egyptian Co-blue scratch-decorated and shoe-shaped vessels, also dating to the Abbasid period, possibly suggest a limited trade in natron glass vessels from Egypt. However, plant ash glasses of Egyptian compositional types were not recognised in this period.

10.2 Further Work

There are many avenues for further work which can help to consolidate the conclusions of this thesis. In the first instance, more analyses for the key 8-9th century period are required from Jordan, Syria and Egypt to confirm some of the trends identified here. This project has proposed that the Levantine glass industry contracted in the 8th century, however, large assemblages of Levantine glass dating to the 8th century have been found from Raya and Raqqa that, at first consideration, do not appear to fit a contraction within the industry. Potential explanations were proposed in Chapter 9 and included the existence of an unknown primary glass production site on the Levantine coast which would match the composition of Raqqa Type 3 and which was not initially affected by the natron shortage. Potential sites might include primary production at Beirut, where production of Levantine type glass from the Roman period has already been recognised (Paynter 2006; Henderson 2013), or currently unrecognised natron glass production at a site such as Tyre, which may have been started with the relocation of glass workers from Palestine by Caliph Hisham. On the other hand, additional production sites within the region of Bet Eli'ezer, which have already been implied from excavated glass waste but not yet analysed (Gorin-Rosen 2000) could have been producing higher soda recipes for export only. Additional analyses of this glass waste could confirm this. In addition, selective re-analysis of the Levantine glass from Raya and Raqqa using higher accuracy techniques for major, minor and trace elements might help to further characterise the glass, with the

potential of ruling out some production sites, or to investigate if the glass was imported cullet rather than fresh production.

In terms of the origins of plant ash technology, the excavation of a Sasanian glass production site would provide useful additional data from which Sasanian production could be better characterised, to further reinforce the conclusion that Eastern Mediterranean plant ash technology had separate technological origins. At the very least, the collection and analysis of surface samples might help to identify the compositional range of glass from within a single production location. Although, such an investigation seems unlikely considering the conditions in Iraq at this time. Furthermore, examples of plant ash glasses from Roman and Byzantine contexts should also be sought, to try and confirm the character and extent of the apparent small scale plant ash glass industry in the region.

For Egypt, there is an acute lack of high quality analyses from consumption sites after the 9th century covering the period of the natron/plant ash transition. While there are excavations from this period, for example Raya (Kawatoko 2007) and Fustat (Kawatoko and Shindo 2010), subsequent analyses were performed using pXRF (Kato et al 2007; 2010A, B), whose lower precision and accuracy does not allow a full characterisation of the glass or close comparison to other known compositional types, as a technique such as LA-ICP-MS or EPMA would allow. Therefore, although the transition has been apparently well dated by the analysis of glass weights, it would be beneficial to know if a similar trend applies to vessels used in domestic settings, and to investigate if the changeover was relatively quick or if a more prolonged transition between technologies occurred, as is seen in Palestine. This would provide additional evidence to the economic explanations for the technological change.

This thesis has recognised a variety of plant ash production groups, however, there are several types identified in data from other regions that have not been fully characterised. This is certainly true for Egyptian glass types, of which only one type has been fully characterised within this project, that of Gratuze and Barrandon's Group 3 (A). As shown in Chapter 9, other Egyptian types are visible within the data from Fustat, and these need further characterisation. Similarly, a number of potential Syrian

compositional groups have been recognised. If these are to be properly defined more samples would be required, ideally from excavations of consumption sites at some of the larger Islamic period cities. Only with more data, in conjunction with excavations of glass workshop sites, can the relationship between the centralised and dispersed models of glass production be investigated in this region.

Finally, the scope of this project was from the 7th to 12th century, ending at the Crusader period in 1099, although some of the analysed samples go beyond this date. Future work could examine how the situation developed in the Crusader period to ascertain if there were changes in the supply of glass during occupation, to investigate if Tyre continued to dominate glass supply in Palestine, or if there was any noticeable importation of European glass types. The political fragmentation of the region may have also encouraged a move to a less centralised model of glass production. Moreover, it has been noted by Ashtor (1992) that a trade in plant ash to Venice commenced during this period. The transport of large quantities of plant ash away from the region might have had detrimental effects on local production, possibly though increased prices, and therefore glass making in Europe may have developed at the expense of the industry in the Levant and Syria.

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Appendices

Appendix A: Re-Analysed Natron Glass Comparative Data

A.1: LA-ICP-MS re-analysed natron glass data from Apollonia and Bet Shean (both Apollonia-type/Levantine I), Bet Eli'ezer (Levantine II) and El Ashmunein (Egypt II). Data by Lankton and Freestone (pers. comms.) Sample and site references at base of table. Wt% for major and minor oxides, the remaining elements as ppm. bdl = below detection limit (see Chapter 5).

Apollonia-type glass												**Major and minor elements as wt %**
Apollonia[1]	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
AP 1	colourless/blue	chunk	15.70	0.89	3.00	71.08	0.04	0.77	0.39	7.41	0.09	0.51
AP 13	yellowed	chunk	11.99	0.58	3.40	74.58	0.05	0.72	0.38	7.62	0.09	0.47
AP 4	yellowed	chunk	12.96	0.50	3.14	74.29	0.05	0.83	0.41	7.17	0.08	0.44
AP 5	colourless/blue	chunk	14.85	0.63	2.65	72.00	0.04	1.01	0.34	7.89	0.06	0.39
AP 9	colourless/blue	chunk	14.88	0.48	3.27	71.91	0.04	0.73	0.48	7.63	0.07	0.40
Bet Shean[2]	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
BS 6831 218	colourless/blue		14.65	0.68	3.13	70.35	0.12	0.90	0.53	8.94	0.08	0.47
BS 6831 222	colourless/blue		14.71	0.67	3.02	70.33	0.14	0.85	0.54	8.98	0.08	0.51
BS 6831 223	colourless/blue		15.39	0.69	3.00	69.99	0.13	0.86	0.61	8.61	0.08	0.49
BS 6831 225	colourless/blue		15.32	0.64	2.95	71.14	0.10	0.89	0.52	7.78	0.08	0.44
BS 6831 235	colourless/blue		14.67	0.64	2.79	70.31	0.12	0.77	0.64	9.35	0.08	0.48
Bet Eli'ezer-type glass												
Bet Eli'ezer[3]	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
BE 6831 1	colourless/blue	chunk	11.61	0.47	3.43	77.22	0.06	0.72	0.38	5.42	0.08	0.49
BE 6831 2	colourless/blue	chunk	13.26	0.53	3.59	74.44	0.07	0.46	0.61	5.81	0.16	0.94
BE 6831 3	green	chunk	12.00	0.55	3.18	75.44	0.07	0.75	0.48	6.72	0.09	0.57
BE 6831 4	yellowed	chunk	10.27	0.50	3.22	77.18	0.07	0.71	0.35	7.07	0.07	0.43
BE 6831 5	yellowed	chunk	10.67	0.52	3.19	76.71	0.07	0.72	0.38	7.09	0.07	0.44
Egypt II												
El Ashmunein[4]	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
ASN 23246	greenish	vessel	13.63	0.53	2.60	71.37	0.09	1.07	0.25	9.12	0.27	0.93
ASN 23247	colourless	vessel	14.72	0.37	1.75	69.80	0.08	1.11	0.17	10.36	0.17	0.67
ASN 23248	greenish	vessel	15.25	0.58	2.42	69.74	0.09	1.13	0.25	9.15	0.28	0.97
ASN 23249	greenish	glass waste	13.98	0.45	2.06	67.76	0.30	0.99	0.25	12.98	0.26	0.85

Apollonia-type glass																
Apollonia[1]	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Se**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**
AP 1	12.8	202	17	34	184	2.1	6.6	n/a	8.0	4.75	1.53	N/A	12.5	402	6.9	60	2.09
AP 13	bdl	170	16	12	193	1.9	5.5	n/a	6.9	4.77	1.24	N/A	9.4	471	8.6	62	2.14
AP 4	6.0	180	15	17	189	1.8	5.9	1.6	8.5	4.77	1.42	N/A	7.3	461	7.5	56	1.94
AP 5	8.5	223	14	13	205	1.8	5.7	n/a	9.2	4.65	1.98	N/A	7.5	479	6.7	38	1.60
AP 9	6.5	173	14	11	185	1.7	5.1	n/a	7.0	4.93	1.72	N/A	8.2	493	7.4	47	1.82
Bet Shean[2]	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Se**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**
BS 6831 218	3.1	318	18	30	205	2.1	7.1	11.1	11.3	4.64	1.42	N/A	9.1	544	8.3	55	1.90
BS 6831 222	1.6	310	19	30	204	2.1	8.8	13.9	13.5	4.65	1.52	N/A	11.3	529	7.9	53	1.95
BS 6831 223	1.1	314	20	32	184	1.7	7.7	6.8	10.6	4.56	1.21	N/A	9.5	516	7.4	53	1.86
BS 6831 225	bdl	314	17	25	191	1.9	6.4	8.6	11.0	4.49	1.44	N/A	11.2	499	7.5	51	1.80
BS 6831 235	10.5	309	19	24	206	2.3	7.5	5.2	11.5	4.64	3.04	N/A	11.5	553	7.7	51	1.79
Bet Eli'ezer-type glass																	
Bet Eli'ezer[3]	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Se**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**
BE 6831 1	23.7	150	16	24	167	1.5	6.1	2.6	13.1	5.30	1.07	N/A	8.7	371	7.2	53	2.11
BE 6831 2	21.4	148	33	38	232	3.3	10.7	20.1	12.1	6.48	1.39	N/A	8.8	359	8.4	79	3.76
BE 6831 3	15.5	169	19	27	210	1.9	7.4	8.1	8.4	5.30	1.14	N/A	8.6	432	7.1	54	2.25
BE 6831 4	8.4	155	13	26	169	0.9	5.6	6.5	7.1	4.53	0.70	N/A	10.0	468	7.9	55	1.87
BE 6831 5	15.3	160	14	25	170	1.1	6.2	6.4	6.9	4.59	0.87	N/A	10.4	460	7.7	55	1.88
Egypt II																	
El Ashmunein[4]	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Se**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**
ASN 23246	4.7	291	37	45	198	3.8	9.0	1.3	18.2	4.67	2.78	33.89	6.0	203	8.0	259	4.61
ASN 23247	2.0	272	23	29	7010	3.5	7.5	0.5	76.1	3.82	0.97	28.48	5.9	178	6.2	132	3.25
ASN 23248	4.0	362	40	46	200	3.8	9.5	0.0	18.4	4.96	0.74	9.21	7.1	204	7.9	279	4.84
ASN 23249	11.2	267	35	35	181	3.4	8.0	1.7	30.0	4.05	0.82	bdl	7.2	191	7.2	222	4.59

Apollonia-type glass															
Apollonia[1]	**MoO**	**Ag**	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**
AP 1	0.21	bdl	bdl	23	n/a	bdl	6.7	15	1.7	6.41	1.27	0.41	1.23	0.19	1.06	0.23
AP 13	0.35	bdl	bdl	26	n/a	bdl	8.0	16	1.9	7.92	1.47	0.47	1.38	0.24	1.37	0.27
AP 4	0.32	bdl	bdl	29	n/a	bdl	7.2	16	1.8	7.24	1.39	0.48	1.40	0.21	1.16	0.24
AP 5	0.11	bdl	bdl	11	n/a	bdl	6.6	16	1.8	6.21	1.25	0.42	1.23	0.19	1.03	0.20
AP 9	0.27	bdl	bdl	20	n/a	bdl	7.1	16	1.8	6.95	1.31	0.43	1.30	0.20	1.18	0.24
Bet Shean[2]	**MoO**	**Ag**	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**
BS 6831 218	0.52	0.10	bdl	27	n/a	bdl	7.4	15	1.8	7.22	1.39	0.34	1.29	0.21	1.22	0.25
BS 6831 222	0.53	0.09	bdl	24	n/a	bdl	7.2	15	1.8	7.14	1.40	0.34	1.26	0.21	1.14	0.23
BS 6831 223	0.58	0.10	bdl	21	n/a	bdl	7.1	15	1.7	6.69	1.34	0.34	1.20	0.21	1.10	0.24
BS 6831 225	0.57	0.07	bdl	21	n/a	bdl	6.8	14	1.7	6.72	1.30	0.33	1.21	0.19	1.10	0.23
BS 6831 235	0.53	bdl	bdl	21	n/a	bdl	7.1	15	1.7	6.68	1.39	0.41	1.29	0.21	1.15	0.22
Bet Eli'ezer-type glass																
Bet Eli'ezer[3]	**MoO**	**Ag**	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**
BE 6831 1	0.30	0.05	bdl	29	n/a	bdl	6.9	15	1.7	6.97	1.26	0.37	1.27	0.19	1.08	0.24
BE 6831 2	0.36	0.11	bdl	19	n/a	bdl	8.4	20	2.1	8.01	1.61	0.44	1.51	0.24	1.28	0.26
BE 6831 3	0.36	0.09	bdl	17	n/a	bdl	7.1	17	1.8	6.85	1.38	0.37	1.25	0.20	1.07	0.22
BE 6831 4	0.28	0.13	bdl	24	n/a	bdl	7.2	15	1.8	7.23	1.29	0.32	1.33	0.22	1.20	0.26
BE 6831 5	0.38	0.10	bdl	26	n/a	bdl	7.2	15	1.8	7.09	1.41	0.31	1.26	0.22	1.17	0.25
Egypt II																
El Ashmunein[4]	**MoO**	**Ag**	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**
ASN 23246	0.22	0.19	0.20	25	0.77	bdl	8.20	17	2.00	7.78	1.48	0.40	1.34	0.21	1.28	0.27
ASN 23247	0.27	0.15	0.12	22	bdl	bdl	6.56	14	1.59	6.16	1.21	0.33	1.08	0.18	0.97	0.20
ASN 23248	0.13	0.21	0.10	21	bdl	bdl	8.37	18	2.05	7.80	1.52	0.42	1.42	0.19	1.19	0.26
ASN 23249	0.21	0.21	0.16	24	bdl	bdl	7.62	17	1.87	6.98	1.42	0.39	1.26	0.20	1.15	0.23

Apollonia-type glass												
Apollonia[1]	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**WO**	**BaO**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AP 1	0.60	0.09	0.59	0.08	1.23	0.08	207	bdl	5.4	bdl	0.87	0.70
AP 13	0.73	0.11	0.64	0.09	1.33	0.11	245	bdl	0.6	bdl	1.10	0.88
AP 4	0.63	0.10	0.64	0.09	1.17	0.08	243	bdl	3.4	bdl	0.95	0.94
AP 5	0.57	0.07	0.51	0.08	0.73	0.03	188	bdl	3.8	bdl	0.68	0.74
AP 9	0.64	0.09	0.57	0.07	0.99	0.06	240	bdl	3.3	bdl	0.82	2.05
Bet Shean[2]	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**WO**	**BaO**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
BS 6831 218	0.69	0.10	0.64	0.09	1.14	0.06	228	bdl	bdl	bdl	0.92	0.99
BS 6831 222	0.67	0.10	0.66	0.09	1.08	0.09	223	bdl	bdl	bdl	0.89	1.01
BS 6831 223	0.63	0.09	0.59	0.08	1.12	0.09	218	bdl	bdl	bdl	0.85	1.08
BS 6831 225	0.63	0.08	0.59	0.09	1.05	0.09	218	bdl	bdl	bdl	0.83	0.92
BS 6831 235	0.63	0.09	0.58	0.08	1.10	0.08	220	bdl	bdl	bdl	0.85	1.16
Bet Eli'ezer-type glass												
Bet Eli'ezer[3]	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**WO**	**BaO**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
BE 6831 1	0.64	0.09	0.59	0.09	1.12	0.10	247	bdl	bdl	bdl	0.95	0.66
BE 6831 2	0.73	0.10	0.73	0.10	1.52	0.15	205	bdl	bdl	bdl	1.32	0.86
BE 6831 3	0.59	0.09	0.61	0.08	1.12	0.11	232	bdl	bdl	bdl	0.92	0.79
BE 6831 4	0.68	0.10	0.63	0.11	1.13	0.08	243	bdl	bdl	bdl	0.96	0.90
BE 6831 5	0.71	0.10	0.62	0.09	1.15	0.09	240	bdl	bdl	bdl	0.93	0.75
Egypt II												
El Ashmunein[4]	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**WO**	**BaO**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
ASN 23246	0.72	0.11	0.85	0.13	4.97	0.09	172	bdl	5.2	bdl	1.79	1.16
ASN 23247	0.57	0.08	0.62	0.09	2.62	0.05	179	bdl	8.2	bdl	1.25	1.91
ASN 23248	0.73	0.11	0.87	0.13	5.28	0.10	168	bdl	4.5	bdl	1.80	1.27
ASN 23249	0.67	0.10	0.69	0.12	4.32	0.09	132	bdl	8.2	bdl	1.59	1.12

1 Samples described in Tal et al 2004; 2 Samples unpublished; 3 Samples described in Freestone et al 2000;
4 Samples described in Bimson and Freestone 1985.

Appendix B: Re-Analysed Plant Ash Glass Comparative Data

B.1 LA-ICP-MS re-analysed plant ash glass data from Banias and Tyre. Data by Phelps and Freestone. Sample references at base of table. Wt% for major and minor oxides, the remaining elements as ppm.

Banias[1]													
									Major and minor elements as wt %				
Sample	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
6831-62-x	light purple	glass chunk	11.62	2.57	0.89	72.95	0.24	0.82	1.65	7.78	0.11	0.83	0.42
6831-47-k	colourless/yellow	glass chunk	11.73	2.48	0.89	72.67	0.24	0.85	1.57	8.11	0.11	0.83	0.41
6831-46-x	colourless	glass chunk	11.80	2.58	0.93	72.51	0.24	0.85	1.68	7.86	0.12	0.88	0.42
6831-53-t	purple	glass chunk	12.16	2.47	0.86	72.85	0.24	0.89	1.62	7.38	0.11	0.91	0.39
6831-55-k	purple/yellow	glass chunk	12.19	2.70	1.06	70.13	0.28	0.87	1.36	9.63	0.14	0.97	0.54
6831-56-r	green	glass chunk	11.06	2.55	1.26	72.12	0.22	0.81	1.79	8.49	0.13	0.95	0.51
6831-57-p	green	glass chunk	11.72	2.42	1.01	70.73	0.27	0.85	1.59	9.82	0.12	0.86	0.48
6831-59-w	colourless/green	glass chunk	11.71	2.63	1.45	70.69	0.22	0.82	1.79	8.51	0.14	1.22	0.67
6831-63-k	green	glass chunk	11.99	2.60	0.94	71.97	0.25	0.84	1.61	8.27	0.12	0.85	0.43
6831-61-t	colourless/purple	glass chunk	12.19	2.54	0.89	72.40	0.24	0.90	1.73	7.55	0.12	0.89	0.43
6831-58-k	light purple	glass chunk	12.06	2.64	1.23	69.50	0.25	0.78	1.34	10.48	0.13	0.77	0.68
Tyre[2]													
Sample	**Colour**	**Material**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
BM7230-3	green	glass chunk	13.29	3.69	1.84	63.33	0.33	0.67	2.35	12.08	0.09	1.59	0.57
BM7230-4	green	glass chunk	12.37	3.71	1.98	62.79	0.34	0.66	2.32	13.46	0.10	1.54	0.58
BM7230-6	colourless	glass chunk	14.08	3.63	1.85	65.83	0.32	0.90	2.32	9.59	0.09	0.75	0.50
BM7230-7	green	glass chunk	11.98	3.83	2.08	63.66	0.33	0.65	2.22	12.85	0.10	1.59	0.56
un-labelled	colourless/purple	glass chunk	10.51	3.15	1.83	65.83	0.27	0.75	1.76	14.09	0.08	1.13	0.48
BM7230-13	yellow	glass chunk	13.04	3.82	2.00	65.07	0.35	0.79	2.33	9.66	0.11	1.99	0.62
BM7230-14	purple	glass chunk	13.25	3.79	1.82	66.45	0.29	0.75	2.29	8.56	0.09	2.01	0.55
BM7230-12	dark blue	glass chunk	11.56	2.86	2.09	65.89	0.34	0.71	2.19	9.62	0.09	0.82	3.28
BM7230-5	brown	glass chunk	14.26	3.25	1.05	67.49	0.45	0.94	2.49	9.37	0.09	0.04	0.46

Banias															**Trace elements as ppm**		
Sample	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**
6831-62-x	9.7	271	26	19	4.1	8.0	11	26	3.5	3.9	10	438	5.8	185	3.3	1.5	bdl
6831-47-k	8.9	264	25	16	4.0	7.9	12	25	3.4	3.4	10	433	5.7	181	3.3	1.8	bdl
6831-46-x	11.6	272	27	16	4.9	9.6	13	28	3.5	3.4	10	454	5.9	189	3.4	2.0	bdl
6831-53-t	13.1	263	25	16	4.3	8.2	13	27	3.6	3.7	10	421	5.5	176	3.2	1.7	bdl
6831-55-k	14.4	208	30	19	5.9	16.6	29	45	4.7	2.5	9	669	6.6	182	3.5	2.1	bdl
6831-56-r	17.7	269	30	34	6.5	13.0	21	27	4.5	3.2	11	472	6.7	188	3.9	2.3	bdl
6831-57-p	10.0	261	26	19	5.2	10.4	14	23	4.3	3.6	11	469	6.5	200	3.6	2.6	bdl
6831-59-w	12.5	282	37	21	9.1	17.5	21	41	5.5	4.2	12	463	6.5	137	4.4	2.5	bdl
6831-63-k	8.5	261	26	17	5.3	10.1	14	28	4.1	3.1	10	451	5.9	188	3.4	1.8	bdl
6831-61-t	11.3	271	26	16	5.4	10.3	15	30	3.9	3.4	10	429	5.7	183	3.3	1.7	bdl
6831-58-k	14.7	196	30	22	6.2	14.8	18	49	4.5	2.2	10	610	7.0	171	3.8	1.9	bdl
Tyre																	
Sample	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**
BM7230-3	7.2	305	25	20	6.4	13.3	89	33	5.0	3.3	16	525	7.1	49	2.1	5.1	bdl
BM7230-4	bdl	293	25	21	6.3	13.3	86	29	5.2	3.2	16	551	7.9	55	2.2	4.9	bdl
BM7230-6	1.3	347	18	15	4.1	12.2	18	26	3.8	3.3	19	534	7.6	52	2.1	1.4	bdl
BM7230-7	bdl	303	25	20	6.4	13.1	81	22	5.2	3.1	15	574	8.5	57	2.4	5.2	bdl
un-labelled	6.1	204	23	15	4.5	10.1	24	21	4.4	3.8	13	563	8.1	51	1.8	4.1	bdl
BM7230-13	1.3	306	34	22	7.6	15.8	96	41	5.9	4.3	18	556	7.7	53	2.4	5.8	bdl
BM7230-14	3.4	291	25	17	7.0	13.3	85	30	5.6	3.2	16	529	6.8	47	2.0	6.1	bdl
BM7230-12	bdl	236	22	18	810.0	28.4	2562	591	9.7	15.2	15	570	8.1	54	2.0	5.7	bdl
BM7230-5	3.4	299	22	23	2.5	16.8	26	48	2.7	2.9	10	547	5.7	53	1.7	1.1	bdl

Banias																**Trace elements as ppm**
Sample	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**
6831-62-x	bdl	11.3	bdl	bdl	114	4.9	9.3	1.09	4.21	0.90	0.22	0.73	0.15	0.88	0.20	0.56	0.07
6831-47-k	bdl	6.7	bdl	bdl	109	4.9	9.4	1.07	4.15	0.79	0.21	0.76	0.14	0.85	0.19	0.54	0.08
6831-46-x	bdl	7.0	bdl	bdl	124	5.2	9.8	1.12	4.36	0.86	0.25	0.82	0.15	0.94	0.18	0.56	0.09
6831-53-t	bdl	5.0	bdl	bdl	106	4.6	9.7	1.03	3.83	0.83	0.22	0.76	0.15	0.84	0.18	0.57	0.07
6831-55-k	bdl	7.1	bdl	bdl	203	5.9	12.0	1.30	4.93	1.03	0.27	1.13	0.16	1.10	0.21	0.60	0.09
6831-56-r	bdl	9.0	bdl	bdl	175	6.1	11.6	1.27	4.99	0.98	0.31	1.15	0.16	1.00	0.22	0.59	0.09
6831-57-p	bdl	4.4	bdl	bdl	112	5.5	10.2	1.14	4.63	0.95	0.28	1.05	0.16	1.01	0.20	0.57	0.09
6831-59-w	bdl	3.5	bdl	bdl	202	7.4	15.0	1.55	6.14	1.13	0.34	1.28	0.18	1.12	0.22	0.63	0.09
6831-63-k	bdl	5.1	bdl	bdl	117	5.2	9.8	1.12	4.31	0.93	0.28	1.07	0.16	0.91	0.19	0.58	0.08
6831-61-t	bdl	3.8	bdl	bdl	116	4.9	9.6	1.06	4.17	0.79	0.27	0.91	0.15	0.89	0.18	0.55	0.08
6831-58-k	bdl	5.8	bdl	bdl	172	6.5	13.3	1.40	5.41	1.05	0.34	1.18	0.16	1.05	0.22	0.59	0.09
Tyre																	
Sample	**Cd**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**
BM7230-3	bdl	8.7	bdl	bdl	366	7.1	12.8	1.67	6.84	1.29	0.30	1.20	0.19	1.16	0.22	0.63	0.08
BM7230-4	bdl	12.4	bdl	bdl	387	7.6	13.7	1.81	7.13	1.46	0.30	1.12	0.19	1.30	0.27	0.62	0.11
BM7230-6	bdl	9.8	bdl	bdl	276	7.5	13.6	1.74	7.18	1.37	0.31	1.11	0.20	1.21	0.25	0.69	0.10
BM7230-7	bdl	12.0	bdl	bdl	393	7.9	14.0	1.85	7.72	1.48	0.35	1.18	0.21	1.30	0.27	0.72	0.10
un-labelled	bdl	11.1	bdl	bdl	336	7.2	13.0	1.67	6.91	1.50	0.31	1.19	0.21	1.20	0.25	0.68	0.09
BM7230-13	bdl	11.7	bdl	bdl	364	7.7	14.9	1.87	7.79	1.66	0.38	1.27	0.22	1.29	0.26	0.69	0.10
BM7230-14	bdl	7.0	bdl	bdl	348	7.0	13.9	1.74	6.87	1.44	0.33	1.13	0.19	1.14	0.23	0.57	0.08
BM7230-12	bdl	14.2	6.1	bdl	339	7.5	13.0	1.76	7.20	1.44	0.28	1.31	0.22	1.19	0.26	0.71	0.11
BM7230-5	bdl	10.9	bdl	bdl	70	7.2	12.5	1.61	6.01	1.19	0.17	0.80	0.16	0.88	0.17	0.42	0.07

Banias										**Trace elements as ppm**	
Sample	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
6831-62-x	0.60	0.09	3.88	0.19	0.63	bdl	bdl	7.71	bdl	1.15	0.48
6831-47-k	0.58	0.08	3.85	0.18	0.73	bdl	bdl	bdl	bdl	1.10	0.48
6831-46-x	0.63	0.09	3.88	0.18	0.64	bdl	bdl	bdl	bdl	1.17	0.51
6831-53-t	0.54	0.09	3.76	0.17	0.78	bdl	bdl	bdl	bdl	1.11	0.50
6831-55-k	0.63	0.10	3.84	0.20	0.20	bdl	bdl	bdl	bdl	1.31	0.65
6831-56-r	0.61	0.10	4.00	0.21	0.42	bdl	bdl	bdl	bdl	1.30	0.53
6831-57-p	0.62	0.10	4.21	0.20	1.27	bdl	bdl	bdl	bdl	1.27	0.49
6831-59-w	0.74	0.09	2.93	0.27	0.31	bdl	bdl	bdl	bdl	1.39	0.53
6831-63-k	0.54	0.10	3.86	0.20	0.66	bdl	bdl	bdl	bdl	1.16	0.50
6831-61-t	0.54	0.09	3.77	0.18	0.72	bdl	bdl	bdl	bdl	1.09	0.49
6831-58-k	0.67	0.09	3.74	0.22	0.23	bdl	bdl	bdl	bdl	1.35	0.67
Tyre											
Sample	**Yb_2O_3**	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
BM7230-3	0.58	0.08	1.12	0.11	0.47	bdl	bdl	bdl	bdl	0.96	0.57
BM7230-4	0.67	0.09	1.21	0.13	0.51	bdl	bdl	16.3	bdl	1.06	0.60
BM7230-6	0.60	0.08	1.19	0.13	0.22	bdl	bdl	bdl	bdl	1.09	0.46
BM7230-7	0.75	0.10	1.31	0.13	0.47	bdl	bdl	bdl	bdl	1.14	0.56
un-labelled	0.69	0.09	1.15	0.11	0.50	bdl	bdl	bdl	bdl	0.96	0.47
BM7230-13	0.73	0.09	1.18	0.13	0.61	bdl	bdl	509.0	bdl	1.06	0.55
BM7230-14	0.54	0.08	1.06	0.12	0.59	bdl	bdl	19.6	bdl	0.93	0.53
BM7230-12	0.73	0.10	1.26	0.12	0.19	bdl	bdl	48.0	bdl	1.07	0.49
BM7230-5	0.50	0.06	1.30	0.10	0.07	bdl	bdl	1.4	bdl	1.28	0.77

1 Samples from Banias, Israel, secondary glass workshop, 11^{th}-13^{th} century. Samples and site described in Freestone et al 2000

2 Samples from Tyre, Lebanon, primary production site, 10^{th}-11^{th} century. Samples and site described in Freestone 2002

Appendix C: Sample Descriptions

C.1. Individual descriptions of the samples used in this project. Further details at base of table.

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
Ahihud, Moshav Ahihud, Gorin-Rosen in Porat and Getzov 2010												
AH 3746 01	A-3746	10	101	-	-	-	-	pale blue	N-2	Umayyad	8th	2
AH 3746 02	A-3746	16	111	-	7.3	bowl	tonged	greenish blue	N-3	Umayyad	8th	2
AH 3746 03	A-3746	16	111	-	7.4	bowl	-	greenish blue	N-Outlier	Umayyad	8th	2
AH 3746 04	A-3746	16	113	-	-	wine goblet	-	pale blue	N-2	Umayyad	8th	2
AH 3746 05	A-3746	16	113	-	-	bowl	tonged	green	N-3	Umayyad	8th	2
AH 3746 06	A-3746	16	113	-	-	-	-	pale blue	N-3	Umayyad	8th	2
AH 3746 07	A-3746	18	112	-	-	stem lamp	pinched	yellowish green	N-1	Umayyad	8th	2
AH 3746 08	A-3746	25	129	-	7.1	wine goblet	-	pale blue	N-2	Umayyad	8th	2
AH 3746 09	A-3746	30	139	-	-	bowl	tonged	green	N-3	Umayyad	8th	2
AH 3746 10	A-3746	30	139	-	-	stem lamp	pinched	greenish blue	N-4	Umayyad	8th	2
AH 3746 11	A-3746	30	139	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
AH 3746 12	A-3746	30	141	-	7.2	small bottle	-	pale blue	N-2	Umayyad	8th	2
AH 3746 13	A-3746	30	141	-	-	-	-	pale blue	N-2	Umayyad	8th	2
Ashdod-Yam, Ashdod-Yam Castle, Ouahnouna 2014												
AY 2844 01	A-2844	957	5306	-	30.4	bowl	-	colourless with brownish tinge	removed	Umayyad-Abbasid	8th- early 11th	-
AY 2844 02	A-2844	816	4078	-	28.6	bottle	-	greenish	P-1	Mid Abbasid	9th-10th	4
AY 2844 03	A-2844	801	4016	-	28.12	bottle	-	colourless with greenish tinge	P-1	Abbasid-Fatimid	9th-early - 11th	4-5
AY 2844 04	A-2844	809	4032	-	28.15	bottle	-	colourless	P-1	Abbasid-Fatimid	9th-early - 11th	4-5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
AY 2844 05	A-2844	835	4094	-	29.1	jug	-	greenish-bluish	N-1	Abbasid-Fatimid	9th-early - 11th	4-5
AY 2844 06	A-2844	919	5052	-	28.13	bottle	blue applied trails	colourless with yellowish tinge	P-1	Fatimid	11th	5
AY 2989 01	A-2989	1252	6301	-	32.1	bowl	tonged	greenish	N-3	Umayyad-Abbasid	late 8th	3
AY 2989 02	A-2989	1093	5971	-	35.2	stirring rod	-	yellowish	N-3	Umayyad-Abbasid	8th-10th	4
AY 2989 03	A-2989	1212	6149	-	29.2	bottle	-	greenish	N-3	Mid Abbasid	9th-10th	4
AY 2989 04	A-2989	1177	6062	-	28.4	bottle	-	colourless with greenish tinge	P-1	Mid Abbasid	9th-10th	4
AY 2989 05	A-2989	1018	5895	-	28.9	bottle	tooled	greenish blue	N-3	Mid Abbasid	9th-10th	4
AY 2989 06	A-2989	1224	6195	-	32.4	bowl	tonged	colourless with greenish tinge	P-1	Mid-Abbasid	9th-10th	4
AY 2989 07	A-2989	1158	6030	-	34.1	lamp	-	colourless with greenish tinge	P-1	Mid-Abbasid	9th-10th	4
AY 2989 08	A-2989	1224	6186	-	33.1	miniature bottle	wheel cut	light green	P-4 (P-Outlier)	Mid Abbasid	10th	5
AY 2989 09	A-2989	911	5339	-	33.3	molar flask	wheel cut	dark green	removed	Mid Abbasid	10th	5
AY 2989 10	A-2658	643	2146	-	28.11	bottle	-	colourless with greenish tinge	P-1	Abbasid-Fatimid	th9-early 11th	4-5
AY 2989 11	A-2989	1224	6177	-	28.14	bottle	-	colourless with yellowish tinge	P-1	Abbasid-Fatimid	9th-early 11th	4-5
AY 2989 12	A-2989	1125	5860	-	31.2	bowl	mould blown	colourless with greenish tinge	P-1	Abbasid-Fatimid	9th-early 11th	4-5
AY 2989 13	A-2989	1096	5752	-	31.8	bottle	mould blown	light green	P-1	Abbasid-Fatimid	9th-early 11th	4-5
AY 2989 14	A-2989	1157	6044	-	33.5	bottle	wheel cut	colourless	P-1	Abbasid-Fatimid	late 10th-11th	5
AY 2989 15	A-2989	987	5589	-	28.19	miniature bottle	-	colourless	P-1	Ayyubid-Mamluk	12th-13th	6

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
AY 2989 16	A-2658	609	2057	-	28.1	bottle	-	cobalt blue	removed	Mid Abbasid	9th-10th	4
Bet Shean, Youth Hostel, Katsnelson 2014												
BSH 2885 01	A-2885	88	262	-	12.4	jar	-	pale yellow	P-1	Ayyubid-Mamluk	12th-13th	6
BSH 2885 02	A-2885	-90510	1021	-	11.11	jug	pinched	colourless	P-1	Abbasid	late 8th - 10th	4
BSH 2885 03	A-2885	510	1021	-	n/a	bottle	-	colourless	P-2a	Ayyubid-Mamluk	12th-13th	6
BSH 2885 04	A-2885	510	1021	-	8.4	bowl	-	colourless	P-1	Abbasid	late 8th - 10th	4
BSH 2885 05	A-2885	540	1270	-	n/a	-		very pale green	P-2b	Ayyubid-Mamluk	12th-13th	6
BSH 2885 06	A-2885	540	1270	-	n/a	-		very pale green	N-1	Ayyubid-Mamluk	12th-13th	6
BSH 2885 07	A-2885	540	1273	-	13.3	bottle?	mould blown	colourless w/ blue tinge	P-2b	Ayyubid-Mamluk	12th-13th	6
BSH 2885 08	A-2885	540	1273	-	n/a	-		colourless	P-2b	Ayyubid-Mamluk	12th-13th	6
BSH 2885 09	A-2885	540	1273	-	13.1	bottle with lentoid base		amber	P-2b (P-Outlier)	Ayyubid-Mamluk	12th-13th	6
BSH 2885 10	A-2885	540	1273	-	n/a	large jug		very pale blue	P-2b (P-Outlier)	Ayyubid-Mamluk	12th-13th	6
BSH 2885 11	A-2885	540	1273	-	13.2	bottle	mould blown and trails	very pale blue	P-2b	Ayyubid-Mamluk	12th-13th	6
BSH 2885 12	A-2885	540	1273	-	13.4	Albarello medium jar	mould blown?	colourless	P-2b	Ayyubid-Mamluk	12th-13th	6
Caesarea, Gorin-Rosen forthcoming A												
CEA 6194 01	n/a	10560	38391	-	1	beaker	tonged	light green	P-Outlier	Abbasid	9th-10th	4
CEA 6194 02	n/a	10262	34168	-	1	flask	tonged	purple and colourless	P-1	Abbasid-Fatimid	9th-early 11	4-5
CEA 6194 03	A-6194	10560	38727	-	1	bottle		'smokey' blue	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 04	A-6194	10494	37777	-	2	bottle		colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 05	A-6194	10494	37777	-	3	bottle		light green	P-Outlier	Abbasid-Fatimid	9-early 11	4-5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
CEA 6194 06	A-6194	10494	37777	-	4	beaker		colourless with green tinge	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 07	n/a	10522	37856	-	1	6-sided bottle	moulded	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 08	n/a	10560	38689	-	1	bowl	tonged	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 09	n/a	10560	38631	-	2	bottle		'smokey' blue	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 10	n/a	10560	38407	-	3	small bottle	tooled/ engraved	'smokey' blue	P-3	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 11	n/a	10494	37808	-	2	bottle	incised/ engraved	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 12	n/a	10494	37808	-	3	bottle	mould blown	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 13	n/a	10560	38391	-	4	bowl/beaker/flask	mould blown	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 14	n/a	10494	37808	-	5	bowl		colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
CEA 6194 15	n/a	10494	37808	-	6	bottle	tonged/pressed	colourless with purple tinge	P-1	Abbasid-Fatimid	9-early 11	4-5
Caesarea, South Western Zone, Winter forthcoming A												
CEA W2S3 01	Insula W2S3 (area 1)	113	20529	-	26.6	disc - glass weight?	stamped	greenish?	N-1	late Byzantine/ Umayyad	7th-8th	1
CEA W2S3 02	Insula W2S3 (area 1)	604	54130	-	26.3	large vessel - jug/jar/oil lamp		pale blue	N-1	late Byzantine/ Umayyad	7th-8th	1
CEA W2S3 03	Insula W2S3 (area 1)	3892	20686	-	24.6	bottle	mould blown		N-3	Mid-Abbasid	9th-10th century	4
CEA W2S3 04	Insula W2S3 (area 1)	114	20660 209999	6	25	bottle		cobalt blue	P-4	Mid-Abbasid	9th-10th	4
Ha-Bonim, Ha-Bonim Castle, Katsnelson forthcoming A												
HB 3032 01	A-3032	3033	30107	30	1.6	bowl/beaker/oil lamp		brown glass	N-2	Umayyad	8th	2

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
HB 3032 02	A-3032	3002	300135	30	1.14	bottle		greenish blue	N-3	Umayyad	8th	2
HB 3032 03	A-3032	1044	10290	10	3.1	bottle		dull greenish blue	N-3	Early Abbasid	late 8th/ early 9th	3
HB 3032 04	A-3032	1046	10167	10	3.2	bottle		green	P-2a	Early Abbasid	late 8th/ early 9th	3
HB 3032 05	A-3032	1044	1E+07	10	2.2	cylindrical bowl		greenish blue	N-3	Mid Abbasid	9th-10th	4
HB 3032 06	A-3032	1007	10035	10	3.4	juglet		blue	P-1 Co (P-Outlier)	Mid Abbasid	9th-10th	4
HB 3032 07	A-3032	1095	10556	10	3.5	bottle	mould blown	colourless with light purple patch	P-1	Mid Abbasid	9th-10th	4
HB 3032 08	A-3032	1095	10556	10	3.5	bottle	mould blown	colourless with light purple patch	P-1	Mid Abbasid	9th-10th	4
HB 3032 09	A-3032	1042	10185	10	3.6	bottle	mould blown or tooled?	colourless	P-3	Mid Abbasid	9th-10th	4
HB 3032 10	A-3032	1044	10290	10	3.11	bowl/bottle?	mould blown	yellowish brown	N-3	Mid Abbasid	9th-10th	4
HB 3032 11	A-3032	3078	30201	30	1.8	cylindrical deep bowl	trailing	colourless	P-1	Mid Abbasid	9th-10th	4
HB 3032 12	A-3032	3002	300132	30	1.7	bowl	stamped/tonged	colourless	P-1	Mid Abbasid	9th-10th	4
HB 3032 13	A-3032	3033	30107	30	1.11	bowl		light green	P-1	Mid Abbasid	9th-10th	4
HB 3032 14	A-3032	3036	30166	30	1.18	bottle		colourless	P-1	Mid Abbasid	9th-10th century	4
HB 3032 15	A-3032	3002	30013	30	1.12	bowl/bottle		colourless	P-3	Abbasid-Fatimid	9th-11th	5
HB 3032 16	A-3032	3032	30087	30	2.1	bottle/bowl	mould blown	purple swirls,	P-1	Abbasid-Fatimid	9th-early 11th	4-5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
HB 3032 17	A-3032	3117	30263	30	2.2	bottle	mould blown	yellowish-colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
HB 3032 18	A-3032	3023	30021	30	2.4	bottle/bowl	mould blown	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
HB 3032 19	A-3032	1035	10326	10	3.12	??	-	green	P-1	Abbasid-Fatimid	9th-11th	4-5
HB 3032 20	A-3032	1007	10073	10	2.1	shallow bowl	-	colourless	P-1 (P-Outlier)	Abbasid-Fatimid	10-early 11	5
HB 3032 21	A-3032	1079	10452	10	2.2	bowl	-	colourless with light purple streaks	P-1	Abbasid-Fatimid	10-early 11	5
HB 3032 22	A-3032	1056	10203	10	3.7	jar	-	dull light green	P-1	Abbasid-Fatimid	10-11th (to Mamluk)	5
HB 3032 23	A-3032	1042	10354	10	3.8	bottle	-	colourless	P-1	Fatimid-Crusader	10-11th C (continues later)	6
Jerusalem, City of David Giv'ati Car Park, Winter forthcoming B												
JER 3835 01	A-3835	468	2796	-	5.5	lamp	-	colourless with greenish tinge	N-1	Late Byzantine/ Umayyad	7-8th	1
JER 3835 02	A-3835	285	1442	-	5.6	lamp	-	pale blue	N-1	Late Byzantine/ Umayyad	7-8th	1
JER 3835 03	A-3835	133	1656	-	6.3	bottle	applied blue trails	colourless	N-1	Late Byzantine/ Umayyad	late 6th-8th	1
JER 3835 04	A-3835	465	2941	-	6.5	bottle	-	pale green	N-1	Late Byzantine-Umayyad	late 6th-7th	1
JER 3835 05	A-3835	386	1747	-	8.1	beaker	-	greenish blue	N-1	early-mid Abbasid?	8th-10th	3
JER 3835 06	A-3835	44	1246	-	8.3	bowl?	tonged	colourless	P-1	early-mid Abbasid?	8th-10th	3
JER 3835 07	A-3835	98	334	-	9.2	bottle	-	blue	P-4	mid Abbasid	9-10th	4

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
JER 3835 08	A-3835	468	3E+07	-	9.6	large bottle/jar	-	greenish blue	P-Outlier	mid Abbasid	9-10th	4
JER 3835 09	A-3835	229	1568	-	9.7	lamp		pale blue	P-1	mid Abbasid	9-10th	4
JER 3835 10	A-3835	23	2329	-	9.3	unknown vessel	mould blown	greenish blue	P-Outlier	Abbasid-Fatimid	10-11th C	5
JER 3835 11	A-3835	368	2456	-	9.4	unknown vessel	relief cut	colourless with greenish tinge	P-1	Abbasid-Fatimid	10-11th C	5
JER 3835 12	A-3835	13	1286	-	7.3	window pane	-	greenish blue	removed	n/a	n/a	n/a
JER 3835 13	A-3835	13	1286	-	3.4	window pane	-	greenish blue	removed	n/a	n/a	n/a
JER 3835 14	A-3835	533	4434	-	6.6	stirring rod	-	pale blue	removed	n/a	n/a	n/a
JER 3835 15	A-3835	98	334	-	8.2	beaker	-	colourless	removed	n/a	n/a	n/a
Jerusalem, The Old City: Wilson's Arch and Great Causeway, Katsnelson forthcoming B												
JER 5124 01	A-5124	1515	2130	-	6.4	bottle?	-	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th century	1
JER 5124 02	A-5124	1515	2130	-	6.6	bottle	applied decoration	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 03	A-5124	1515	2130	-	7.7	bottle	-	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 04	A-5124	1507	2118	-	7.11	trick bottle	-	light greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 05	A-5124	5020	50211	-	8.4	lamp	-	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 06	A-5124	23002	230040	-	8.7	bottle	tonged	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 07	A-5124	20013	200100	-	13.1	bottle/beaker/lamp	mould blown	pale blue	N-2	Late Byzantine/ Umayyad	late 7th-8th	2
JER 5124 08	A-5124	20021	200131	-	13.8	alembic	-	greenish-blue	N-1	Late Byzantine/ Umayyad	late 7th-8th	1
JER 5124 09	A-5124	1710	2336	-	-	window	-	blue	removed	Late Byzantine/ Umayyad	7th-8th	2

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
JER 5124 10	A-5124	1710	2336	-	-	bottle	-	pale green	N-3	Late Byzantine/ Umayyad	7th-8th	2
JER 5124 11	A-5570-2009	3108	32032	-	-	wineglass	-	greenish-blue	N-1	Late Byzantine/ Umayyad	7th-8th	1
JER 5124 12	A-5124	1502	2112	-	-	bottle	trails	pale greenish-blue	N-1	Late Byzantine/ Umayyad	7th-8th	1
JER 5124 13	A-5124-2007	1512	2127	-	-	oil lamp	-	green	N-1	Umayyad	8th?	1
JER 5124 14	A-5124-2007	1512	2127	-	-	bottle?	trails	pale blue	N-1	Umayyad	8th?	1
JER 5124 15	A-5124-2007	1512	2127	-	-	oil lamp	-	pale blue	N-1	Umayyad	8th?	1
JER 5124 16	A-5124-2007	1512	2127	-	-	jug	-	pale blue	N-1	Umayyad	8th?	1
JER 5124 17	A-5124-2007	1512	2127	-	-	oil lamp	-	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 18	A-5124-2007	1710	2338	-	-	bowl/beaker/oil lamp	-	green	N-2	Umayyad	8th?	2
JER 5124 19	A-5124-2007	1710	2338	-	-	bottle	pinched	greenish-blue	N-2	Umayyad	8th?	2
JER 5124 20	A-5124-2007	1528	2182	-	-	window	-	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 21	A-5124	1526	2168	-	-	bottle	pinched	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 22	A-5124	1712	-	-	-	oil lamp	-	greenish-blue	N-2	Umayyad	8th?	2
JER 5124 23	A-5124	1515	2130	-	-	oil lamp	-	greenish-blue	N-1	Umayyad	8th?	1

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
JER 5124 24	A-5124	1515	2130	-	-	bottle	-	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 25	A-5124	1515	2130	-	-	bowl shaped oil lamp	-	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 26	A-5124	1529	2174	-	-	window	-	greenish-blue	N-1	Umayyad	8th?	1
JER 5124 27	A-5124	20017	200135	-	15.1	window	-	green	N-1	Late Byzantine/ Umayyad	7th	1
JER 5124 28	A-5124	5020	50211	-	3.2	bowl	mould blown	pale green	N-3 Mn	Mid Abbasid	9th-10th	4
JER 5124 29	A-5124	1516	2132	-	6.8	bottle	mould blown	olive green	N-1	Abbasid	9th-10th	4
JER 5124 30	A-5124	1516	2132	-	6.10	bottle	mould blown	greenish blue	N-2	Abbasid	9th-10th	4
JER 5124 31	A-5570-2009	3108	32032	31	10	beaker/ cylindrical bottle	-	yellowish green	P-3	Abbasid-Fatimid	9th-11th	4-5
Nahal Shoval, Winter forthcoming C												
NS 6362 01	A-6362	695	5361	-	2.1	bowl/beaker	-	light greenish blue	N-2	Umayyad	8th	2
NS 6362 02	A-6362	593	5183	-	2.2	bowl/beaker	-	olive green	N-2	Umayyad	8th	2
NS 6362 03	A-6362	314	3028	-	2.9	bottle/jug	applied trails, same colour	greenish blue	N-3	Umayyad	8th	2
NS 6362 04	A-6362	709	5383	-	2.8	bottle/jar	-	light greenish blue	N-Outlier	Umayyad	8th	2
NS 6362 05	A-6362	709	5383	-	2.13	stirring rod	applied wound trail - olive green	light blue	N-3	Umayyad	8th	2
NS 6362 06	A-6362	610	5206	-	3.4	bowl/beaker	tonged	colourless	P-1	Mid Abbasid	9th-10th	4
NS 6362 07	A-6362	323	3048	-	3.1	bowl/beaker	tonged	greenish blue	N-3	Abbasid	9th-10th	4
NS 6362 08	A-6362	321	3035	-	3.2	unknown vessel	tonged	colourless	N-3 Mn	Abbasid	9th-10th	4
NS 6362 09	A-6362	321	3035	-	3.3	unknown vessel	tonged	greenish blue	N-3	Abbasid	9th-10th	4
NS 6362 10	A-6362	598	5207	-	3.7	bowl/beaker?	-	greenish blue	N-Outlier	Abbasid-Fatimid	9th-11th	4-5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
Ramla, Gorin-Rosen forthcoming B												
RAM 3592 01	A-3592	62	162	-	1.2	wineglass	-	greenish	N-1	Umayyad	8th	1
RAM 3592 02	A-3592	109	293	-	1.1	horseshoe shape	-	greenish	removed	Umayyad/Abbasid	late 8th?	3
RAM 3592 03	A-3592	131	312	-	2.4	shoe shaped bottle	-	blue	N-3 Co	Abbasid-Fatimid	9th-11th	4-5
RAM 3592 04	A-3592	138	351	-	2.6	bottle	-	colourless	P-1	Abbasid-Fatimid	9h-11th	4-5
RAM 3592 05	A-3592	138	351	-	2.8	bottle	mould blown	colourless	P-1	Abbasid-Fatimid	9th-11th	4-5
RAM 3592 06	A-3592	138	340	-	2.9	small bottle	wheel cut	colourless	P-3	Abbasid-Fatimid	10th-11th	5
Ramla, Danny Mass Street, Katsnelson 2016												
RAM 3897 01	A-3847	233	4277	-	2.5	bottle	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 3897 02	A-3847	204	4066	-	2.4	jar or lamp	trail	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 3897 03	A-3847	228	4456	-	1.8	lamp with wick tube	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 3897 04	A-3847	228	4325	-	1.9	bottle?	wheel cut	colourless	P-3	Abbasid-Fatimid	10th-11th	5
RAM 3897 05	A-3847	228	4325	-	1.4	bottle	-	blue	P-4	Abbasid-Fatimid	10th-11th	5
RAM 3897 06	A-3847	261	4497	-	2.3	bowl	tonged	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 3897 07	A-3847	228	4325	-	1.3	beaker	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 3897 08	A-3847	214	4314	-	2.9	bottle	engraved decoration	colourless with greenish tinge	P-1	Abbasid-Fatimid	10th-11th	5
Ramla, Ma'asiyaha Junction, Gorin-Rosen 2013												
RAM 4740 01	A-4740	112	1119	-	1.8	horseshoe shaped object	-	pale greenish blue	N-3	Umayyad-Abbasid transition	8th-9th	3
RAM 4740 02	A-4740	100	1029	-	1.3	bottle	wheel cut	colourless	P-3	Abbasid-Fatimid	10th-11th	5
RAM 4740 03	A-4740	102	1009	-	1.1	deep bowl	-	blue	N-3	Abbasid-Fatimid	10th-11th	5
RAM 4740 04	A-4740	102	1016	-	1.2	ampoule	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
RAM 4740 05	A-4740	112	1119	-	1.6	vessel	mould blown	colourless	P-2a	Umayyad-Abbasid transition	8th-9th	3
RAM 4740 06	A-4740	136	1176	-	1.9	large jar	-	very pale greenish yellow	P-1	Crusader	13th	6
RAM 4740 07	A-4740	112	1119	-	-	-	-	very pale blue	N-1	Umayyad-Abbasid transition	8th-9th	3
RAM 4740 08	A-4740	116	1128	-	-	-	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 4740 09	A-4740	116	1128	-	1.7	flask	-	pale blue	N-3	Abbasid-Fatimid	10th-11th	5
RAM 4740 10	A-4740	116	1128	-	-	-	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 4740 11	A-4740	116	1128	-	-	-	-	pale blue	P-Outlier	Abbasid-Fatimid	10th-11th	5
RAM 4740 12	A-4740	142	1210	-	1.4	bottle	facet cut	colourless	P-3	Abbasid-Fatimid	10th-11th	5
RAM 4740 13	A-4740	102	1016	-	1.5	vessel	facet cut	colourless	P-3	Fatimid	11th	5
Ramla, Lod-Na'an railroad track, Gorin-Rosen 2010B												
RAM 4768 01	A-4768	131	1195	-	-	-	wheel cut	very pale greenish blue	N-3	beginning of Abbasid period	late 8th	3
RAM 4768 02	A-4768	131	1133	-	22.1	bowl	-	greenish blue	N-3	beginning of Abbasid period	late 8th	3
RAM 4768 03	A-4768	520	3151	-	22.2	bowl	-	greenish blue	N-3	beginning of Abbasid period	late 8th	3
RAM 4768 04	A-4768	119	1066	-	22.9	bottle	wheel cut	colourless	P-1	Abbasid	mid-8th-10th	4
RAM 4768 05	A-4768	544	3176	-	22.8	bottle	wheel cut	colourless	P-3	Abbasid	mid-8th-10th	4
RAM 4768 06	A-4768	548	3211	-	22.10	unique horn-like	wheel cut	colourless	P-1	Abbasid	mid-8th-10th	4
RAM 4768 07	A-4768	611	3421	-	22.5	bottle	-	green	N-3	Abbasid	mid-8th-10th	4

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
RAM 4768 08	A-4768	621	3399	-	22.6	bottle	-	blue	P-4	Abbasid	mid 8-10th	4
RAM 4768 09	A-4768	600	3319	-	22.3	thimble-like jar	-	blue	P-4	Abbasid	mid 8-10th	4
RAM 4768 10	A-4768	566	3153	-	22.7	bowl	wheel cut	colourless	P-3	Abbasid	mid 8-10th	4
RAM 4768 11	A-4768	125	1168	-	22.4	ampoule	-	colourless	P-1	Abbasid	mid 8-10th	4
Ramla, Ha-Nevi'im Nursery School, Gorin-Rosen 2011												
RAM 5947 01	A-5947	112	1096	-	14.1	bowl	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 02	A-5947	112	1096	-	14.2	-	mould blown	greenish blue	N-3	Umayyad	8th	2
RAM 5947 03	A-5947	112	1096	-	14.3	small bottle	-	greenish blue	N-Outlier	Umayyad)	8th	2
RAM 5947 04	A-5947	112	1096	-	14.4	bottle	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 05	A-5947	112	1096	-	14.5	bottle	-	pale blue	N-3	Umayyad	8th	2
RAM 5947 06	A-5947	112	1096	-	14.6	bottle	-	yellowish green	N-3	Umayyad)	8th	2
RAM 5947 07	A-5947	112	1096	-	14.7	bottle	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 08	A-5947	112	1096	-	14.8	bottle	-	pale blue	N-3	Umayyad	8th	2
RAM 5947 09	A-5947	112	1096	-	14.9	everted jar	-	greenish blue	N-2	Umayyad	8th	2
RAM 5947 10	A-5947	112	1096	-	14.10	conical lamp	-	greenish blue	N-3	Umayyad)	8th	2
RAM 5947 11	A-5947	112	1096	-	14.11	mixing rod	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 12	A-5947	112	1096	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 13	A-5947	105	1064	-	15.8	jar	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 14	A-5947	112	1102	-	15.1	bowl	-	pale green	N-1	Umayyad	8th	2
RAM 5947 15	A-5947	112	1102	-	15.3	cylindrical cup	mould blown	greenish blue	N-3	Umayyad	8th	2
RAM 5947 16	A-5947	112	1102	-	15.4	cup or bowl		greenish blue	N-3	Umayyad	8th	2
RAM 5947 17	A-5947	112	1102	-	15.5	cup or bowl	-	greenish yellow	P-3 (Outlier)	Abbasid	mid 8-9th	3
RAM 5947 18	A-5947	112	1102	-	15.6	-	pinched	greenish blue	N-3	Umayyad	8th	2
RAM 5947 19	A-5947	114	1104	-	15.7	bottle	-	greenish blue	N-3	Umayyad	8th	2

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
RAM 5947 20	A-5947	114	1094	-	-	-	-	pale blue	N-3	Umayyad	8th	2
RAM 5947 21	A-5947	114	1094	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 22	A-5947	114	1094	-	-	pilgrim flask	-	pale blue	N-Outliers	Umayyad	8th	2
RAM 5947 23	A-5947	114	1094	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 24	A-5947	114	1094	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 25	A-5947	114	1094	-	-	-	-	greenish blue	N-3	Umayyad	8th	2
RAM 5947 26	A-5947	102	1029	-	13.1	low bowl	-	greenish yellow	P-1	Mid Abbasid	9th-10th	4
RAM 5947 27	A-5947	109	1071	-	16.2	-	-	colourless	P-1	Abbasid -Fatimid	9th-11th	4
RAM 5947 28	A-5947	100	1014	-	16.4	cylindrical cup	-	pale purple	P-1	Fatimid - Crusader?	11th-12th	6
RAM 5947 29	A-5947	103	1037	-	16.5	square bottle	wheel cut	colourless	P-3	Mid Abbasid	9th-10th	4
RAM 5947 30	A-5947	109	1071	-	16.3	jug or juglet	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
RAM 5947 31	A-5947	109	1071	-	16.6	bottle	wheel cut	colourless	P-3	Abbasid Fatimid	10th-11th	5
Ramla, Ha-Etzel Street, Winter 2013												
RAM 6297 01	A-6297	543	2192	-	36.2	small bowl	-	colourless with greenish tinge	P-1	Abbasid	mid 8th-10th	4
RAM 6297 02	A-6297	519	2128	-	36.3	small bowl	-	light greenish blue	P-1	Abbasid	mid 8th-10th	4
RAM 6297 03	A-6297	543	2192	-	36.4	beaker	-	colourless with bluish tinge	P-1	Abbasid	mid 8th-10th	4
RAM 6297 04	A-6297	166	1185	-	37.2	bottle	-	light greenish blue	N-1	Abbasid	mid 8th-10th	4
RAM 6297 05	A-6297	553	2259	-	37.3	bottle	-	cobalt blue	P-4	Abbasid	9th-10th	4

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
RAM 6297 06	A-6297	166	1185	-	37.7	unknown vessel	scratch decorated	blue	N-3 Co	Abbasid	9th-10th	4
RAM 6297 07	A-6297	536	2229	-	37.8	square section bottle	mould blown	colourless	P-3	Abbasid	mid 8th-10th	4
RAM 6297 08	A-6297	129	1107	-	37.10	inkwell	-	colourless	P-1	Abbasid	9th-10th	4
RAM 6297 09	A-6297	536556	2229	-	38.1	large plate	-	light greenish blue	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 10	A-6297	536	2156	-	38.2	large plate	-	light greenish blue	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 11	A-6297	536	2156	-	38.3	large plate	-	green	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 12	A-6297	143	1120	-	38.4	large jar	-	colourless with greenish tinge	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 13	A-6297	536	2156	-	38.5	bowl	-	green	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 14	A-6297	536556	2229	-	38.6	unknown vessel	-	light olive green	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 15	A-6297	536	2156	-	39.1	large bottle	-	light greenish blue	P-1	Abbasid-Fatimid	10th-11th	5
RAM 6297 16	A-6297	537	2144	-	39.3	small jar	-	colourless	P-1	Abbasid-Fatimid	10th-11th	5
Ramla, Ha-Hez Street, Winter 2015												
RAM 6490 01	A-6490	132	1102	-	1.1	footed bowl	-	greenish blue	N-2	Umayyad	8th	2
RAM 6490 02	A-6490	119	1109	-	-	horse shoe shape	-	greenish blue	N-3	Umayyad	8th	2
RAM 6490 03	A-6490	127	1084	-	-	horse shoe shape	-	greenish blue	N-3	Umayyad	8th	2
RAM 6490 04	A-6490	141	1155	-	1.3	miniature bottle	-	light bluish green	N-3	Umayyad-Abbasid transition	mid-late 8th?	3
RAM 6490 05	A-6490	119	1187	-	1.8	beaker	-	colourless with yellowish tinge	P-1	Abbasid	9th-10th	4
RAM 6490 06	A-6490	119	1187	-	1.11	bottle	-	light green	P-1	Abbasid	9th-10th	4

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
RAM 6490 07	A-6490	142	1166	-	1.14	bottle	-	cobalt blue	P-4	Abbasid	9th-10th	4
RAM 6490 08	A-6490	131	1070	-	1.15	bottle	-	cobalt blue	P-4	Abbasid	9th-10th	4
RAM 6490 09	A-6490	119	1109	-	-	bottle	-	cobalt blue	P-4	Abbasid	9th-10th	4
RAM 6490 10	A-6490	138	1101	-	1.6	bowl	mould blown	green	N-3	Abbasid-Fatimid	9-early 11	4-5
RAM 6490 11	A-6490	146	1129	-	1.13	square section bottle	mould blown	colourless	P-3	Abbasid-Fatimid	9-early 11th	4-5
RAM 6490 12	A-6490	119	1105	-	-	-		colourless	removed			8
Sepphoris, Moshav Zippori, Gorin-Rosen 2010C												
SEP 3791 01	A-3791	103	1016	-	16.1	bowl	-	very pale blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 02	A-3791	103	1016	-	16.2	small bowl or wineglass	-	very pale blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 03	A-3791	108	1036	-	16.3	wineglass	-	very pale blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 04	A-3791	103	1016	-	16.4	wineglass	-	pale yellowish green	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 05	A-3791	103	1016	-	16.5	wineglass	trails	colourless with pale green tinge	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 06	A-3791	103	1016	-	16.6	wineglass	-	olive green	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 07	A-3791	103	1016	-	16.8	bottle	-	pale bluish green	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 08	A-3791	103	1016	-	16.9	bowl shaped oil lamp	-	greenish blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 09	A-3791	103	1016	-	16.10	bowl shaped oil lamp	-	green-olive green	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 10	A-3791	103	1016	-	16.11	stem oil lamp	-	light blue	N-1	Late Byzantine/ early Umayyad	7th	1

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
SEP 3791 11	A-3791	103	1016	-	16.12	stem oil lamp	-	light blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 12	A-3821	303	3007	-	16.7	wineglass	-	pale greenish-blue	N-1	Late Byzantine/ early Umayyad	7th	1
SEP 3791 13	A-3821	500	5006	-	16.15	bottle	-	pale greenish-blue	P-1	Early Abbasid	mid 8-9th	3
SEP 3791 14	A-3821	501	5015	-	16.16	bottle	-	colourless	P-3	Mid Abbasid	9th	4
SEP 3791 15	A-3791	101	1011	-	16.13	bowl	-	pale greenish-blue	P-1	Mid Abbasid	9th-10th	4
SEP 3791 16	A-3821	506	5052	-	16.14	bowl	tonged	very pale greenish-blue	P-2a	Mid Abbasid	9th-10th	4
Tel Rosh, Winter forthcoming D												
TR 6055 01	A-6055	119	1040	-	1	bottle	-	'smokey' pale blue	N-1	Umayyad	7th-8th	1
TR 6055 02	A-6055	223	1268	-	2	bottle	-	yellowish	P-Outlier	Umayyad-Early Abbasid	8th-9th	3
TR 6055 03	A-6055	184	1254	-	4	oil lamp	-	greenish blue	N-1	Umayyad	7th-8th	1
TR 6055 04	A-6055	164	1146	-	3	bottle	applied decoration	light blue	N-2	Umayyad-Abbasid transition?	8th-9th?	3
Tiberias, Roman Theatre, Gorin-Rosen forthcoming C												
TIB 5583 01	A-5583	1209	10381	18	-	bowl/bottle	pinched decorated	greenish blue	N-4	Late Byzantine/ Umayyad	7th-8th	1
TIB 5583 02	A-5583	2133	12281	168	36.1	stirring rod	-	light greenish blue	N-1	Umayyad	7th-8th	1
TIB 5583 03	A-5583	2250	12410	170	36.2	bowl	-	light greenish blue	N-1	Umayyad	7th-8th	1
TIB 5583 04	A-5583	1227	105182	45	10.2	bowl/bottle	tonged	greenish blue	N-1	Umayyad	8th	2
TIB 5583 05	A-5583	1227	105181	45	-	bowl	pinched	brown	N-1	Umayyad	8th	2

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
TIB 5583 06	A-5583	1274	10588	26	-	bowl	incised	cobalt blue	N-3 Co	Early Abbasid	8th-9th	3
TIB 5583 07	A-5583	2047	12075	41	10.1	bottle		cobalt blue	P-4	Mid Abbasid	9th-10th	4
TIB 5583 08	A-5583	1317	10834	69	-	bowl	trail decoration	colourless	P-1	Abbasid-Fatimid	9-early 11th	4-5
TIB 5583 09	A-5583	1317	10834	69	-	bottle	-	colourless	P-1	Abbasid-Fatimid	9-early 11th	4-5
TIB 5583 10	A-5583	1317	10834	69	-	bottle / bowl?	-	partly opaque/dull turquoise	removed	Abbasid-Fatimid	9-early 11th	4-5
TIB 5583 11	A-5583	1317	10834	69	-	bowl	-	purple	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 12	A-5583	1398	10869	69	-	bowl shaped oil lamp	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 13	A-5583	1398	10822	69	-	bottle	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 14	A-5583	1288	10666	57	-	oil lamp	-	light blueish green	P-2a	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 15	A-5583	1023	10084	6	-	bottle	-	light green	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 16	A-5583	1023	10084	6	-	cylindrical beaker	engraved	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 17	A-5583	1274	10588	26	-	cylindrical beaker	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 18	A-5583	1279	11055	29	-	bottle	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 19	A-5583	1279	11055	29	-	bottle	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 20	A-5583	1435	10916	29	-	square section bottle	-	light blueish green	P-2a	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 21	A-5583	1228	11773	36	-	bottle	engraved/ facets	colourless	P-3	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 22	A-5583	1535	11217	54	-	bottle	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 23	A-5583	1535	11224	54	-	big bottle	-	colourless with green tinge	P-1	Abbasid-Fatimid	9-early 11	4-5
TIB 5583 24	A-5583	2121	12259	163	36.5	bowl	-	colourless	P-1	Abbasid-Fatimid	9-early 11	4-5

Sample number	License	Locus	Basket	Area[1]	Figure[2]	Form	Decoration	Colour	Compositional Type[3]	Period	Date	Dating Category[4]
TIB 5583 25	A-5583	1342	10975	57	-	cylindrical beaker	incised	colourless	P-1	Abbasid-Fatimid	10th-early 11th	4-5
TIB 5583 26	A-5583	1342	10975	57	-	cylindrical beaker	incised	colourless	P-1	Abbasid-Fatimid	10th-early 11th	4-5
TIB 5583 27	A-5583	1323	107343	45	11.1	bottle	incised	colourless	P-1	Abbasid-Fatimid	10th-early 11th	4-5
TIB 5583 28	A-5583	1232	107344	45	10.3	ewer	-	colourless	P-1	Abbasid-Fatimid	10th-early 11th	4-5
TIB 5583 29	A-5583	1232	107342	45	10.4	bottle	incised	colourless	P-1	Abbasid-Fatimid	10th-early 11th	4-5
TIB 5583 30	A-5583	2119	12256	-	36.3	bowl shaped oil lamp	-	colourless	P-1	Abbasid-Fatimid	10th-11th	4-5

1 This is the location of the site in which the sample was found as given in the excavation report.

2 This is the Figure (and also vessel number) given to the object within the glass report. For the unpublished (forthcoming) reports, numbers may change upon publication

3 N denotes natron groups; P denotes plant ash groups; removed = glass not assigned a group and were omitted from investigation due to colourants.

4 Dating Groups:

1. 7th century, Late Byzantine-Early Umayyad; 2. Early-mid 8th century, Umayyad; 3. Mid-Late 8th century, Early Abbasid

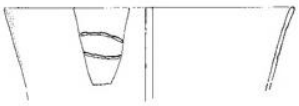
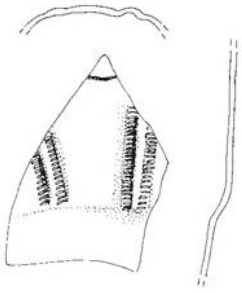
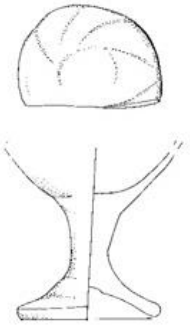
4. 9th century, Mid-Abbasid; 5. 10th-early 11th century, Late Abbasid-Fatimid; 6. 11th-13th century, Fatimid-Crusader

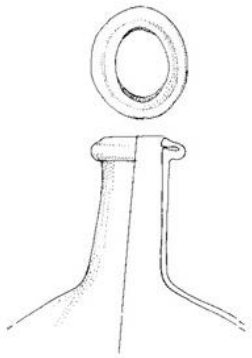
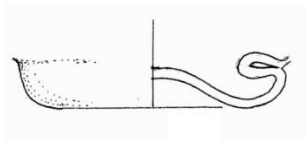
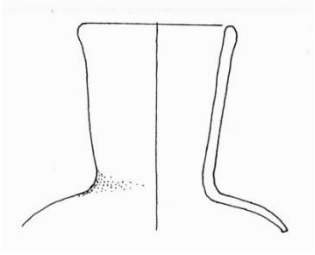
4-5. 9th-early 11th century. Samples are spread evenly over groups 4 and 5.

More details on dating in Chapter 5

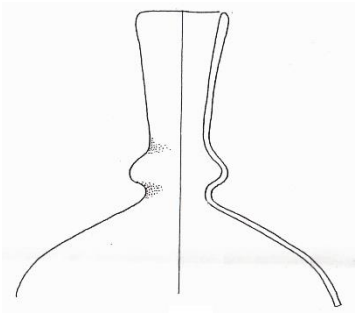
Appendix D: Sample Images

Photos and drawings, where available, of the vessels sampled for this project. Photos taken by author, drawings are from publication and pre-publication reports. Identified compositional group is given with the first image of each vessel.

Ahihud (A-3746)		
 AH 3746-01 / N-2	 AH 3746-02 / N-3	 AH 3746-02
 AH 3746-03 / N-outlier	 AH 3746-03	 AH 3746-04 / N-2
 AH 3746-05 / N-3	 AH 3746-06 / N-3	 AH 3746-07 / N-1
 AH 3746-08 / N-2	 AH 3746-08	 AH 3746-09 / N-3

 AH 3746-10 / N-4	 AH 3746-11 / N-3	 AH 3746-12 / N-2
 AH 3746-12	 AH 3746-13 / N-2	
Ashdod-Yam (A-2844; A-2989; A-2658)		
 AY 2844-01 / N/A	 AY 2844-01	 AY 2844-02 / P-1
 AY 2844-02	 AY 2844-02	 AY 2844-03 / P-1

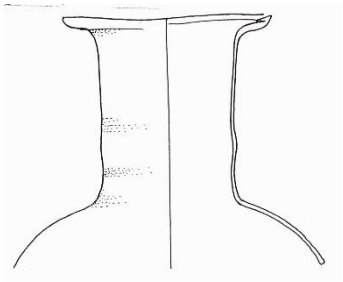
AY 2844-03



AY 2844-03

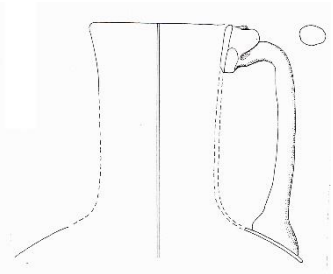
AY 2844-04 / P-1

AY 2844-04



AY 2844-04

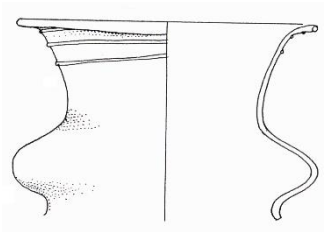
AY 2844-05 / N-1



AY 2844-05

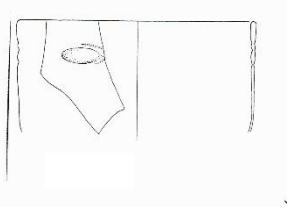
AY 2844-06 / P-1

AY 2844-06



AY 2844-06

AY 2989-01 / N-3



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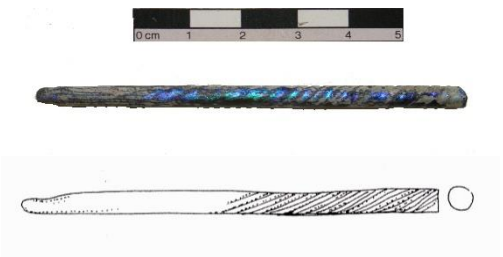
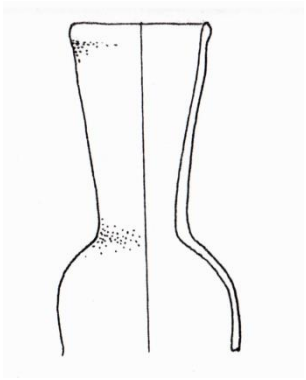


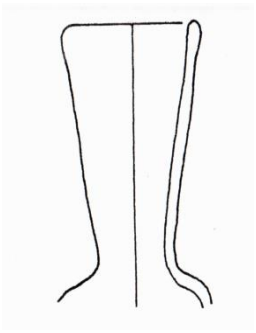
AY 2989-02 / N-3

AY 2989-03 / N-3



AY 2989-03

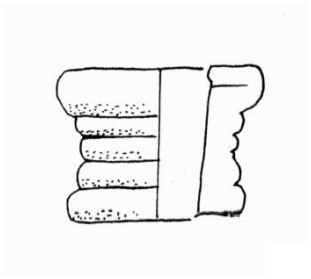
AY 2989-04 / P-1



AY 2989-04

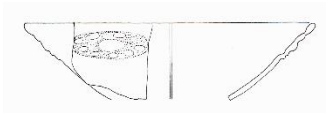
AY 2989-05 / N-3

AY 2989-05 / N-3



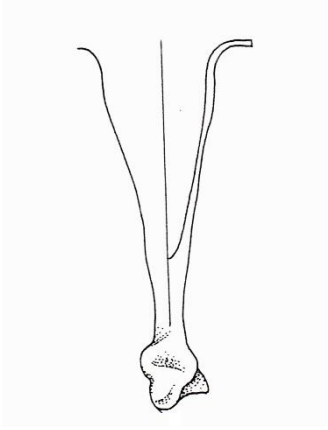
AY 2989-05

AY 2989-06 / P-1



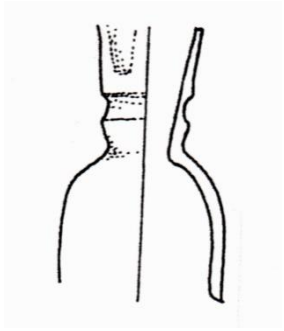
AY 2989-06

AY 2989-07 / P-1



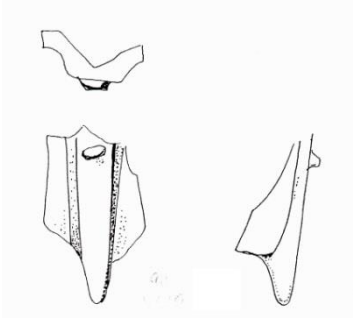
AY 2989-07

AY 2989-08 / P-4? (outlier)



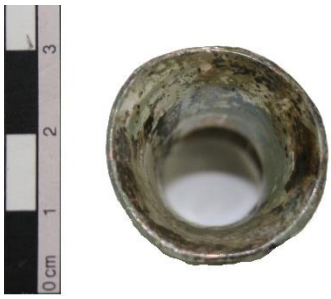
AY 2989-08

AY 2989-09 / N/A

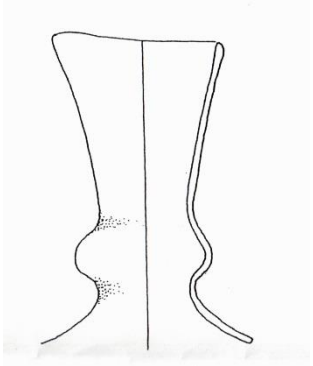


AY 2989-09

AY 2989-10 / P-1

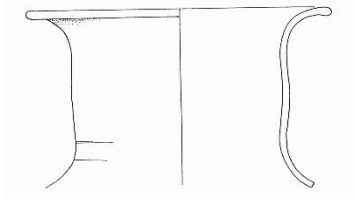


AY 2989-10



AY 2989-10

AY 2989-11 / P-1

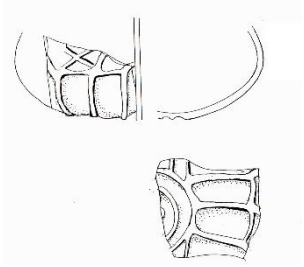
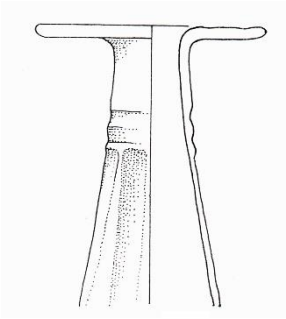
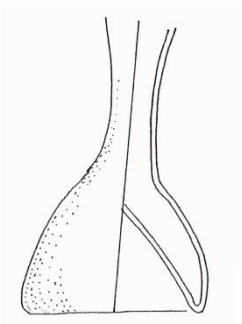
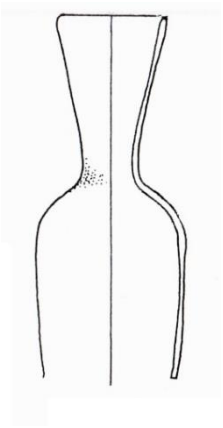
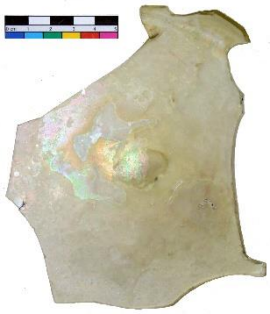


AY 2989-11

AY 2989-12 / P-1

AY 2989-12

AY 2989-13 / P-1

 AY 2989-13	 AY 2989-14 / P-1	 AY 2989-14
 AY 2989-15 / P-1	 AY 2989-15	 AY 2989-16 / N/A
 AY 2989-16	 AY 2989-16	
Bet Shean, Youth Hostel (A-2885)		
 BSH 2885-01 / P-1	 BSH 2885-02 / P-1	

BSH 2885-02

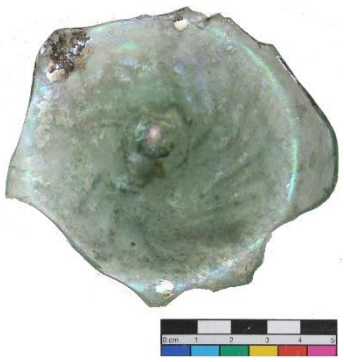
BSH 2885-03 / P-2a

BSH 2885-04 / P-1

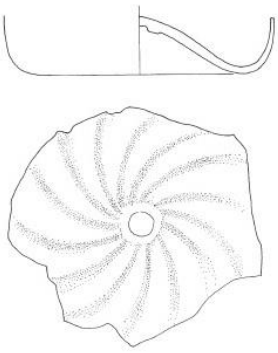
BSH 2885-04

BSH 2885-05 / P-2b

BSH 2885-06 / N-1



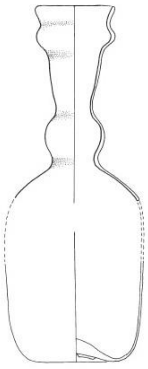
BSH 2885-07 / P-2b



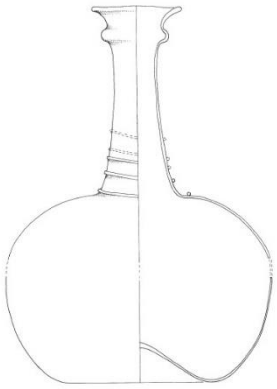
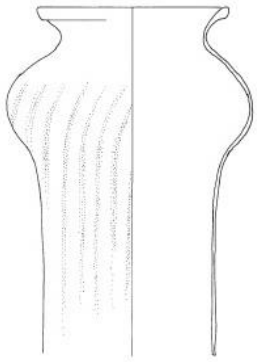
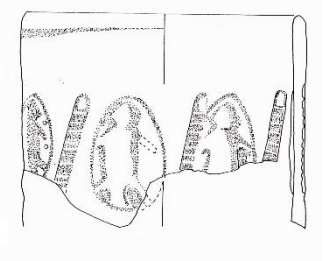
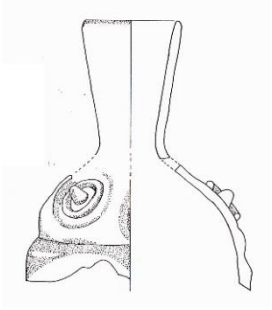
BSH 2885-07

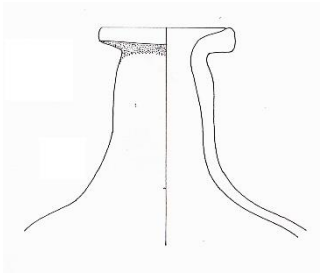
BSH 2885-08 / P-2b

BSH 2885-09 / P-2b (outlier)



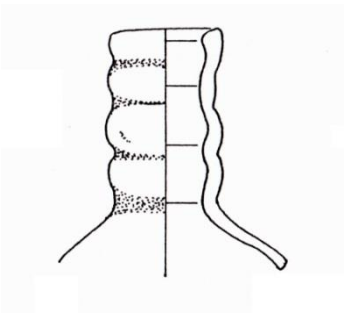
BSH 2885-09

 BSH 2885-11 / P-2b	 BSH 2885-11	 BSH 2885-12 / P-2b
 BSH 2885-12		
Caesarea (A-6194)		
 CEA 6194-01 / P-outlier	 CEA 6194-01	 CEA 6194-02 / P-1
 CEA 6194-02	 CEA 6194-03 / P-1	 CEA 6194-03



CEA 6194-03

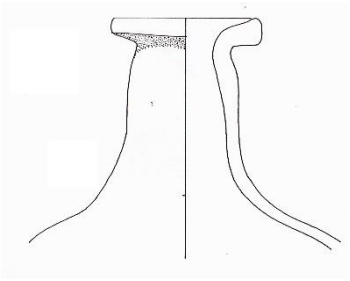
CEA 6194-04 / P-1



CEA 6194-04

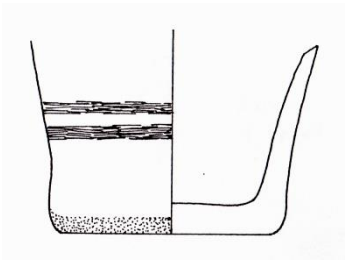
CEA 6194-05 / P-outlier

CEA 6194-05

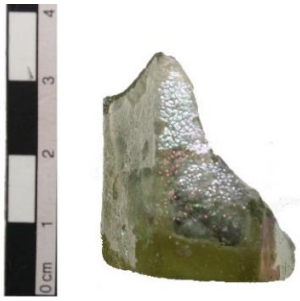


CEA 6194-05

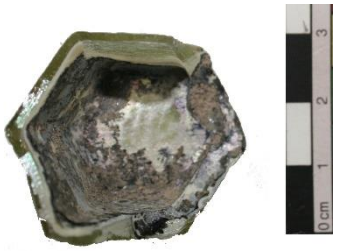
CEA 6194-06 / P-1



CEA 6194-06



CEA 6194-07 / P-1



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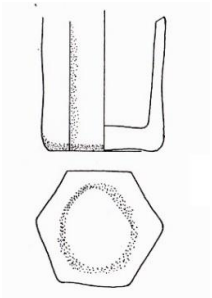
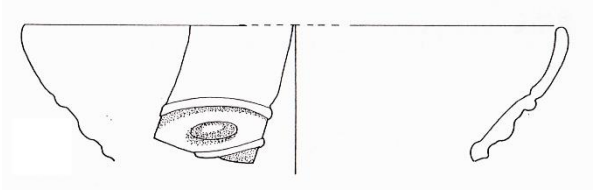


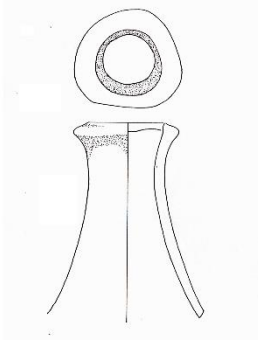
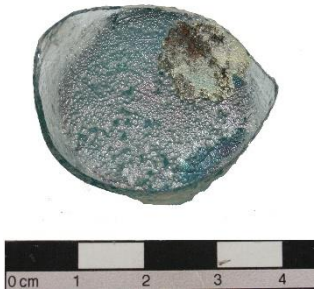
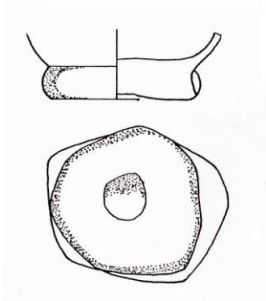
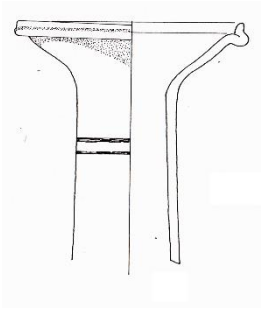
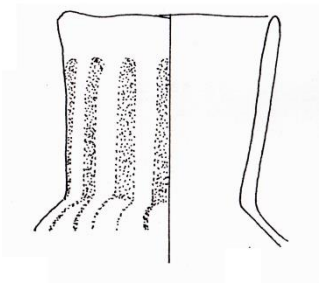
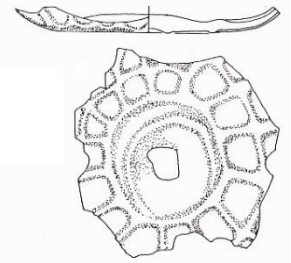
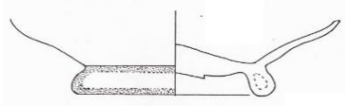
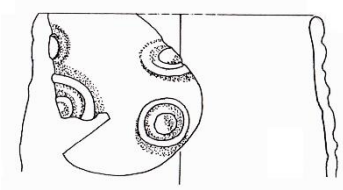
CEA 6194-07

CEA 6194-08 / P-1



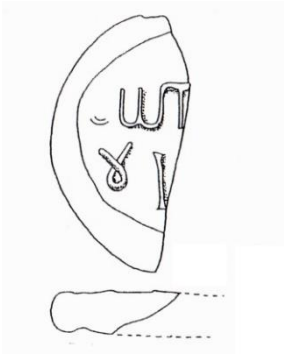
CEA 6194-08

CEA 6194-09 / P-1

 CEA 6194-09	 CEA 6194-09	 CEA 6194-10 / P-3
 CEA 6194-10	 CEA 6194-11 / P-1	 CEA 6194-11
 CEA 6194-12 / P-1	 CEA 6194-12	 CEA 6194-13 / P-1
 CEA 6194-13	 CEA 6194-14 / P-1	 CEA 6194-14
 CEA 6194-14	 CEA 6194-15 / P-1	 CEA 6194-15

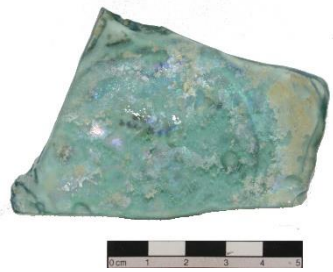
Caesarea, South Western Zone (Insula W2S3)

CEA W2S3-01 / N-1

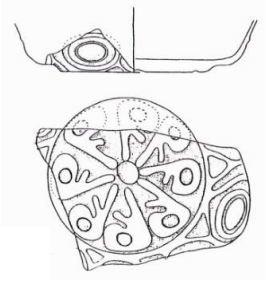


CEA W2S3-01

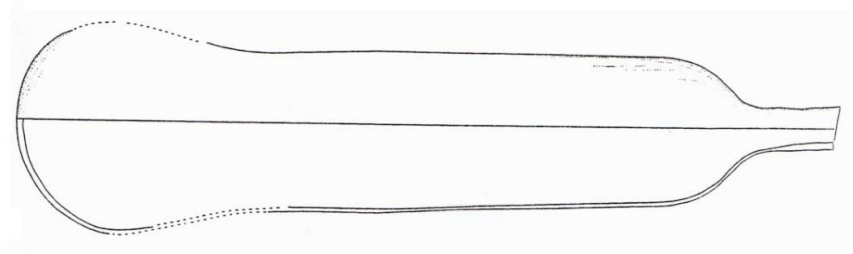
CEA W2S3-02 / N-1



CEA W2S3-03 / N-3

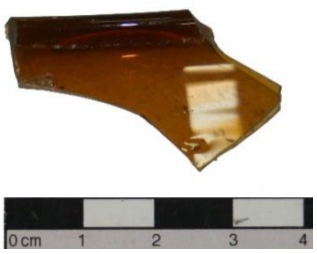


CEA W2S3-03

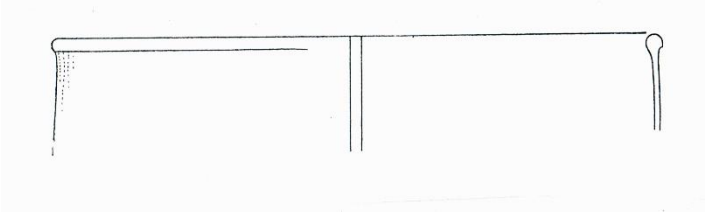


CEA W2S3-04 / P-4

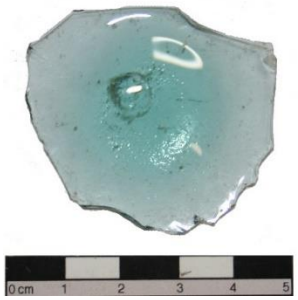
Ha-Bonim (A-3032)



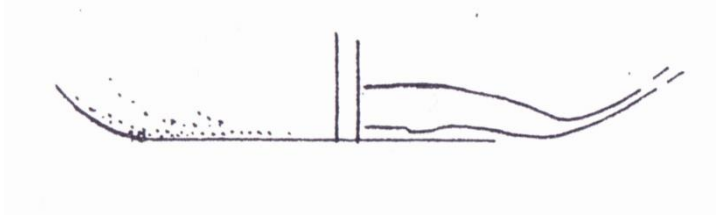
HB 3032-01 / N-2



HB 3032-01

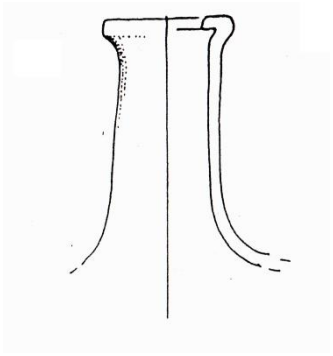


HB 3032-02 / N-3



HB 3032-02

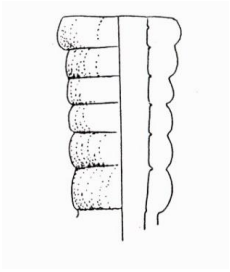
HB 3032-03 / N-3



HB 3032-03

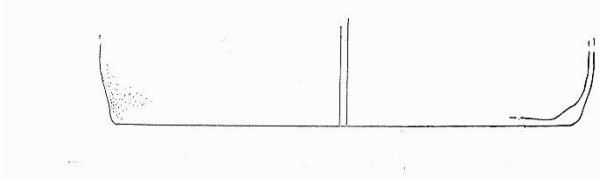
HB 3032-04 / P-2a

HB 3032-04

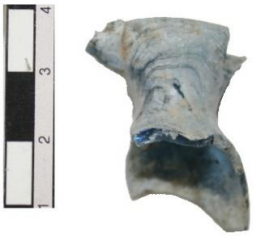


HB 3032-04

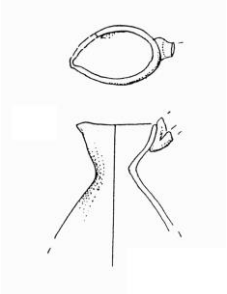
HB 3032-05 / N-3



HB 3032-05

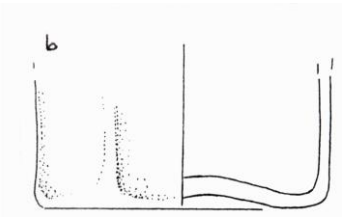


HB 3032-06 / P-1 Co (outlier)



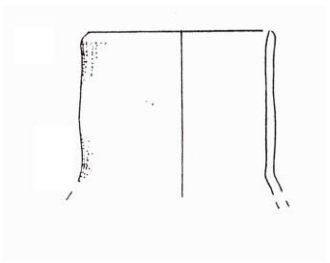
HB 3032-06

HB 3032-07 / P-1

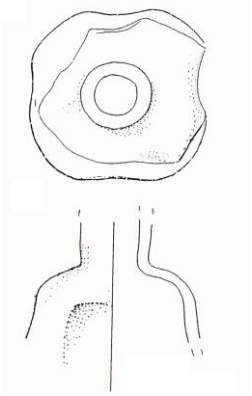


HB 3032-07

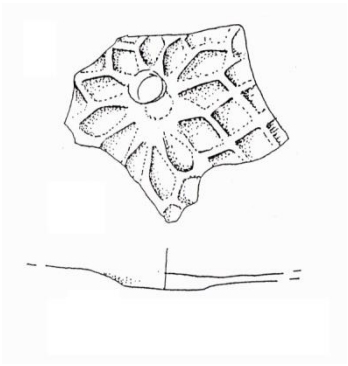

HB 3032-08 / P-1


HB 3032-08

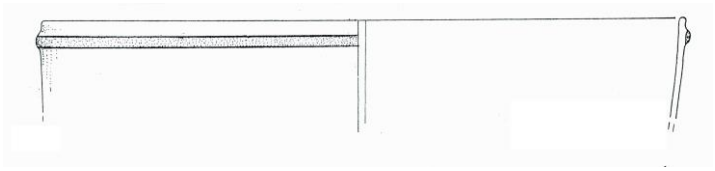

HB 3032-09 / P-3


HB 3032-09

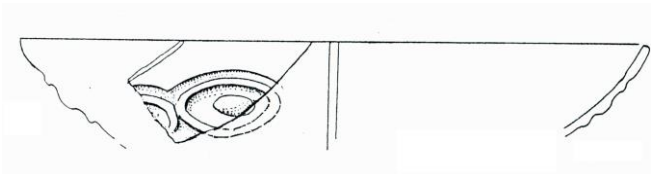

HB 3032-10 / N-3


HB 3032-10

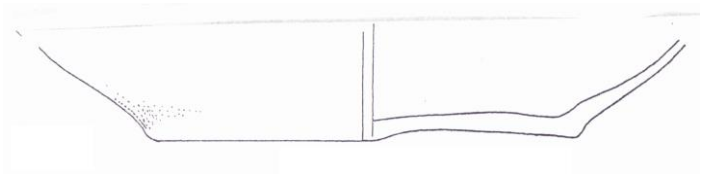

HB 3032-11 / P-1


HB 3032-11

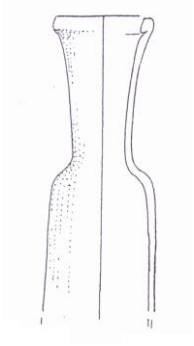

HB 3032-12 / P-1


HB 3032-12


HB 3032-13 / P-1

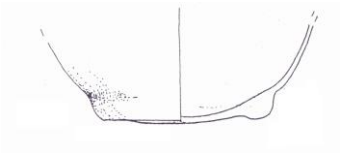

HB 3032-13

HB 3032-14 / P-1

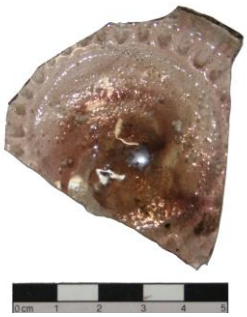


HB 3032-14

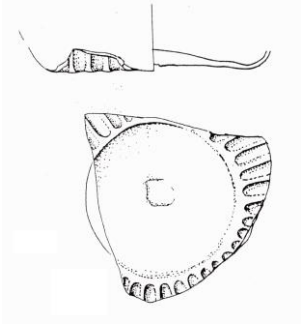
HB 3032-15 / P-3



HB 3032-15

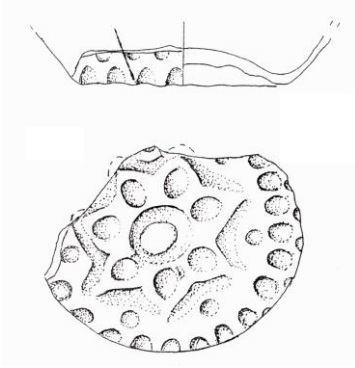


HB 3032-16 / P-1



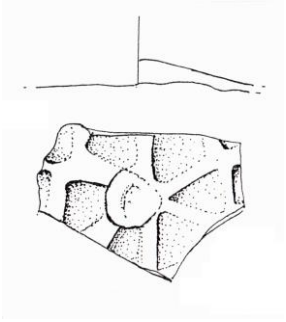
HB 3032-16

HB 3032-17 / P-1



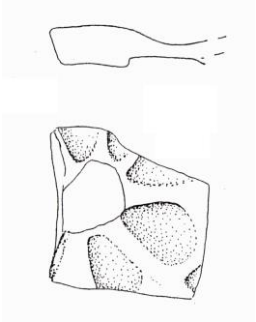
HB 3032-17

HB 3032-18 / P-1



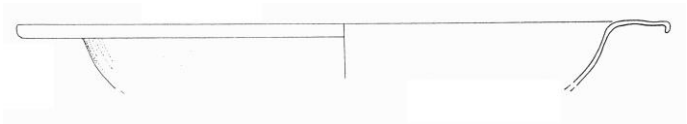
HB 3032-18

HB 3032-19 / P-1



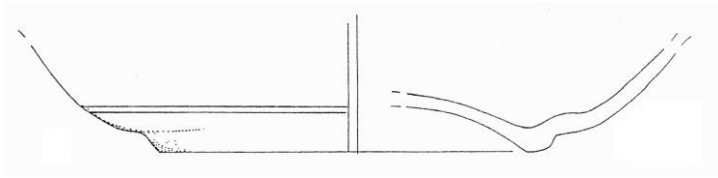
HB 3032-19

HB 3032-20 / P-1 (outlier)



HB 3032-20

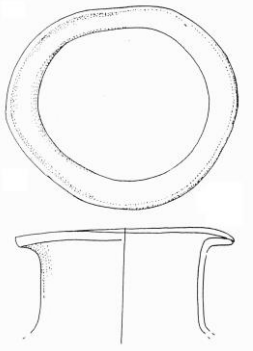
HB 3032-21 / P-1



HB 3032-21

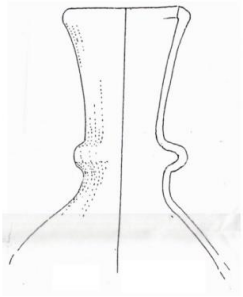
HB 3032-22 / P-1

HB 3032-22



HB 3032-22

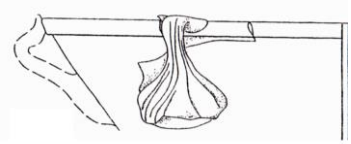
HB 3032-23 / P-1



HB 3032-23

Jerusalem, City of David Giv;ati Car Park (A-3835)

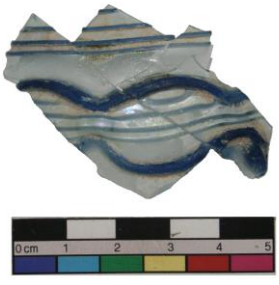
JER 3835-01 / N-1



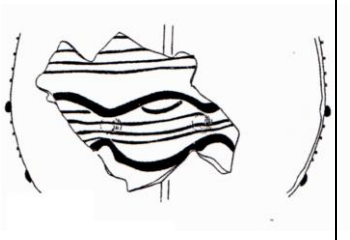
JER 3835-01

JER 3835-02 / N-1

JER 3835-02

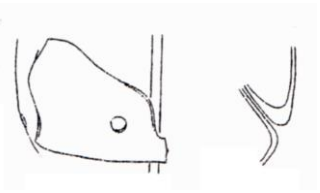


JER 3835-03 / N-1



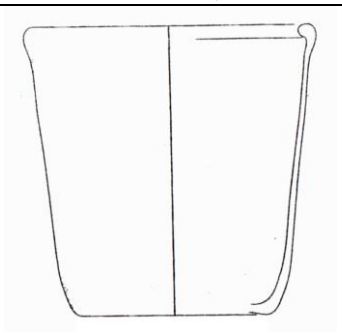
JER 3835-03

JER 3835-04 / N-1

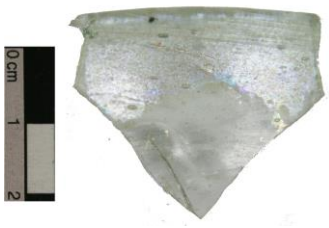


JER 3835-04

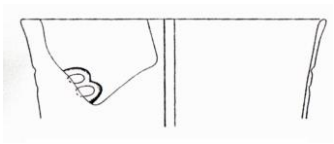
JER 3835-05 / N-1



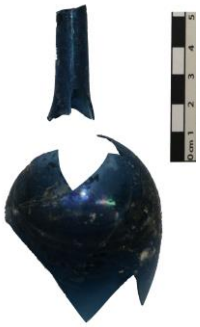
JER 3835-05



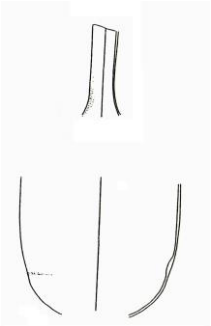
JER 3835-06 / P-1



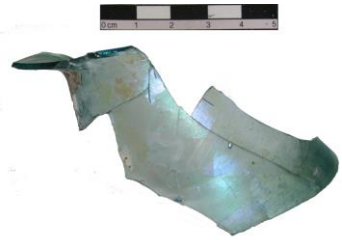
JER 3835-06



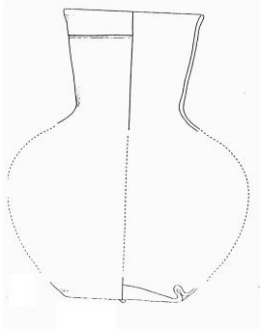
JER 3835-07 / P-4



JER 3835-07

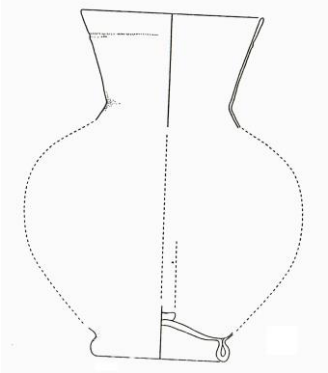


JER 3835-08 / P-outlier



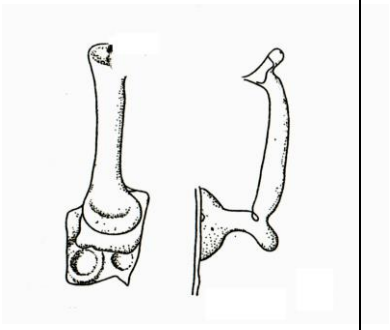
JER 3835-08

JER 3835-09 / P-1



JER 3835-09

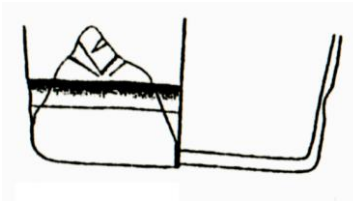
JER 3835-10 / P-outlier



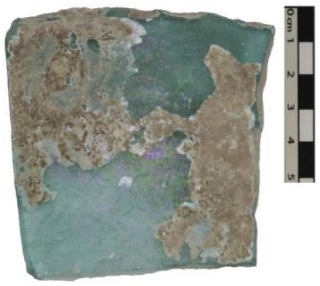
JER 3835-10

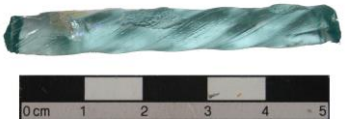

JER 3835-11 / P-1

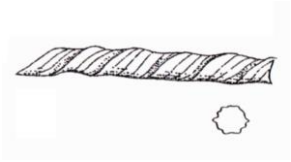

JER 3835-11


JER 3835-11

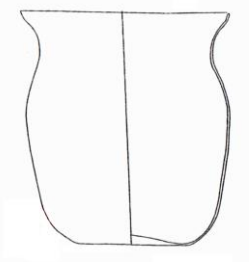

JER 3835-12 / N/A


JER 3835-13 / N/A


JER 3835-14 / N/A

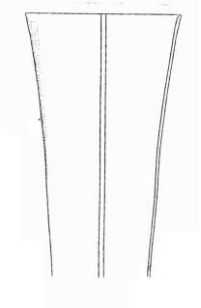

JER 3835-14


JER 3835-15 / N/A

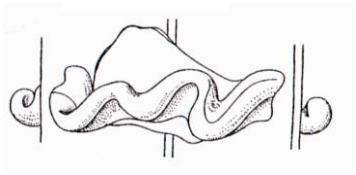

JER 3835-15

Jerusalem, Wilson's Arch and Great Causeway (A-5125; A-5570)


JER 5124-01 / N-1

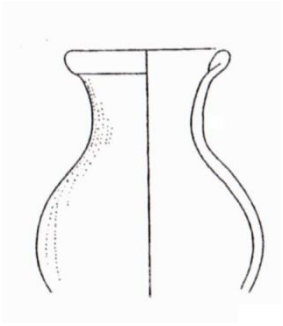

JER 5124-01


JER 5124-02 / N-1



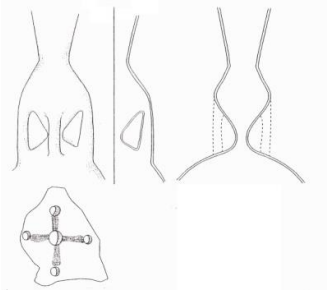
JER 5124-02

JER 5124-03 / N-1



JER 5124-03

JER 5124-04 / N-1

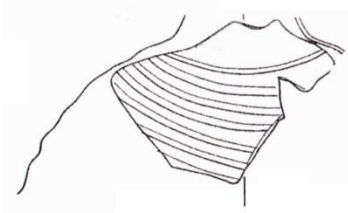


JER 5124-04

JER 5124-05 / N-1

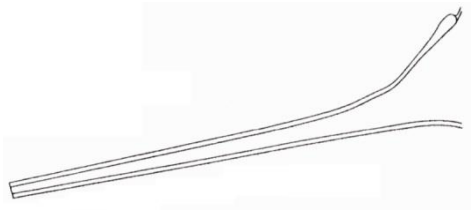
JER 5124-06 / N-1

JER 5124-07 / N-2



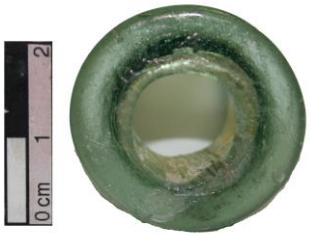
JER 5124-07

JER 5124-08 / N-1



JER 5124-08

JER 5124-09 / N/A



JER 5124-10 / N-3

JER 5124-10

#  JER 5124-11 / N-1	 JER 5124-12 / N-1	 JER 5124-13 / N-1
 JER 5124-14 / N-1	 JER 5124-15 / N-1	 JER 5124-15
 JER 5124-16 / N-1	 JER 5124-17 / N-1	 JER 5124-18 / N-2
 JER 5124-19 / N-2	 JER 5124-20 / N-1	 JER 5124-21 / N-1

JER 5124-22 / N-2

JER 5124-23 / N-1

JER 5124-23

JER 5124-24 / N-1

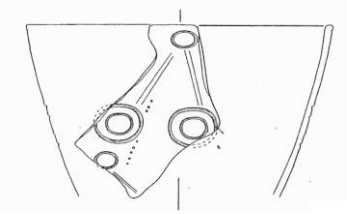
JER 5124-24

JER 5124-25 / N-1

JER 5124-26 / N-1

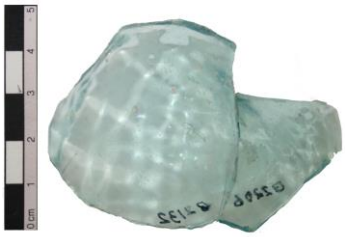
JER 5124-27 / N-1

JER 5124-28 / N-3 Mn

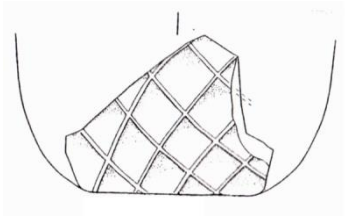


JER 5124-28

JER 5124-29 / N-1



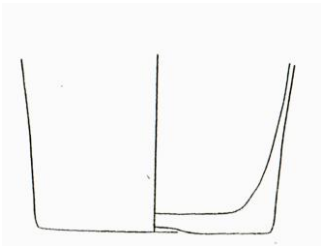
JER 5124-30 / N-2



JER 5124-30

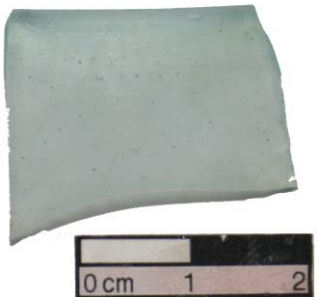
JER 5124-31 / P-3

JER 5124-31

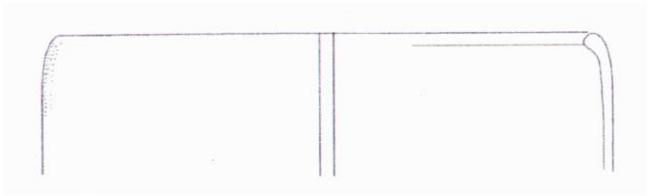


JER 5124-31

Nahal Shoval (A-6362)



NS 6352-01 / N-2

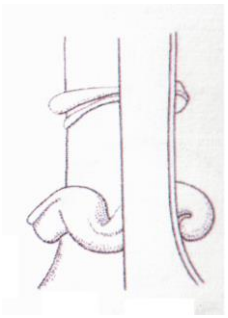


NS 6352-01

NS 6352-02 / N-2

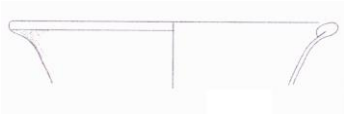
NS 6352-02

NS 6352-03 / N-3



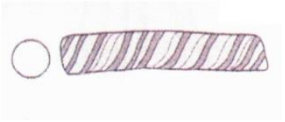
NS 6352-03

NS 6352-04 / N-outlier



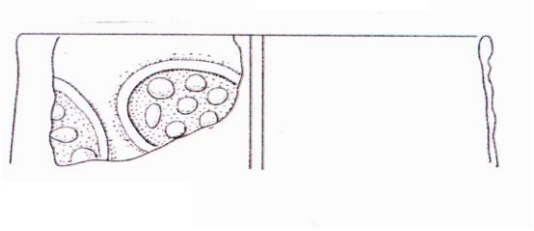
NS 6352-04

NS 6352-05 / N-3

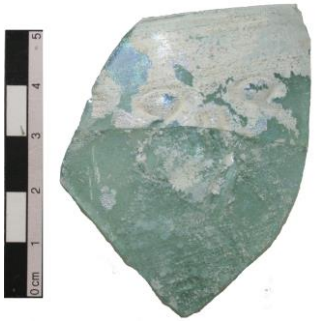


NS 6352-05

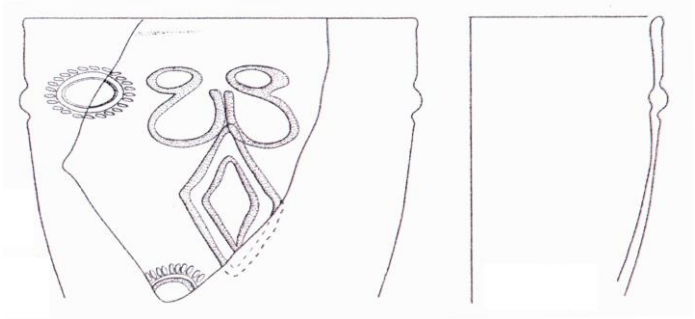
NS 6352-06 / P-1



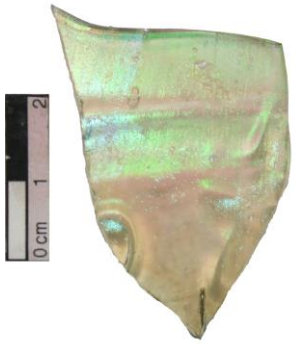
NS 6352-06



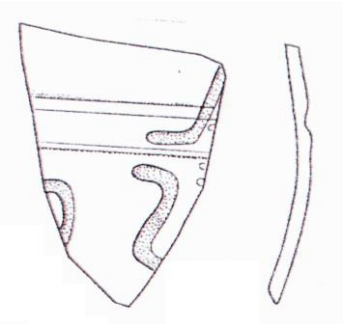
NS 6352-07 / N-3



NS 6352-07

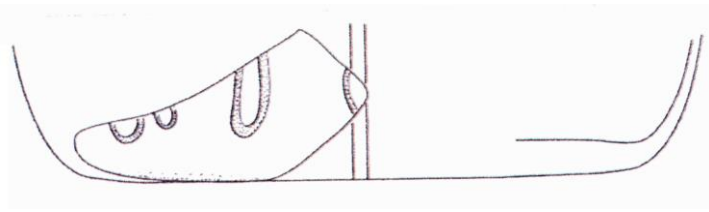


NS 6352-08 / N-3 Mn



NS 6352-08

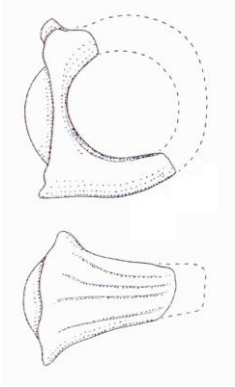
NS 6352-09 / N-3



NS 6352-09

NS 6352-10 / N-outlier

NS 6352-10

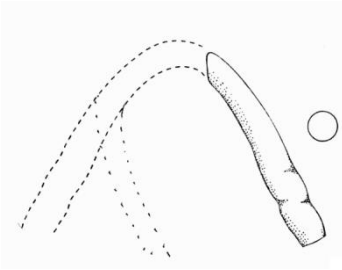


NS 6352-10

Ramla (A-3592)

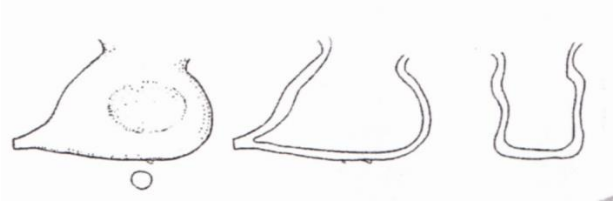
RAM 3592-01 / N-1

RAM 3592-02 / N/A



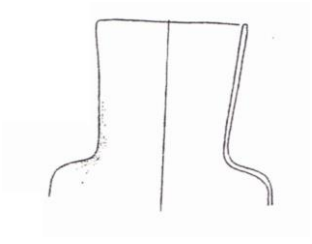
RAM 3592-02

RAM 3592-03 / N-3 Co

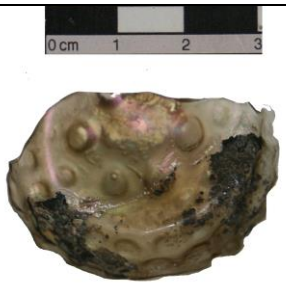


RAM 3592-03

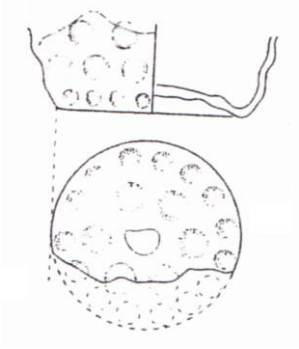
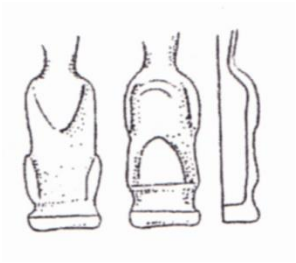
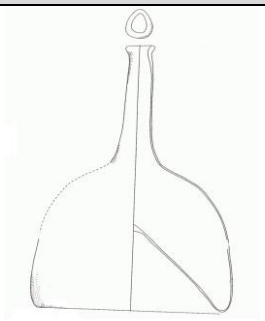
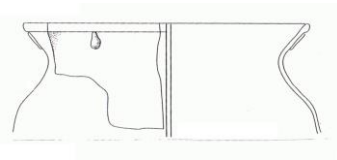
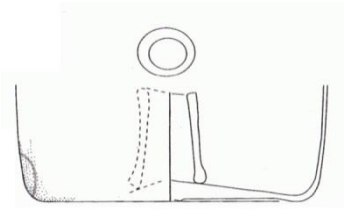
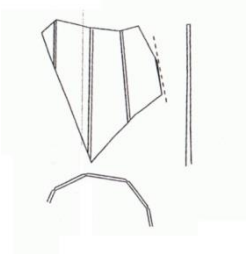
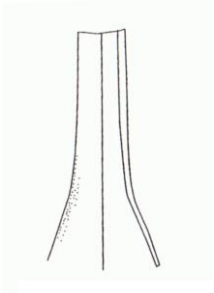
RAM 3592-04 / P-1

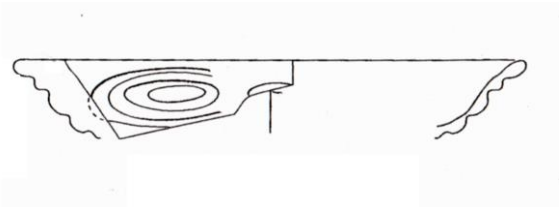


RAM 3592-04



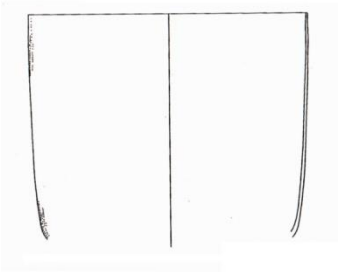
RAM 3592-05 / P-1

 RAM 3592-05	 RAM 3592-06 / P-3	 RAM 3592-06
Ramla, Danny Mass Street (A-3847)		
 RAM 3847-01 / P-1	 RAM 3847-01	
 RAM 3847-02 / P-1	 RAM 3847-02	 RAM 3847-03 / P-1
 RAM 3847-03	 RAM 3847-04 / P-3	 RAM 3847-04
 RAM 3847-05 / P-4	 RAM 3847-05	 RAM 3847-06 / P-1



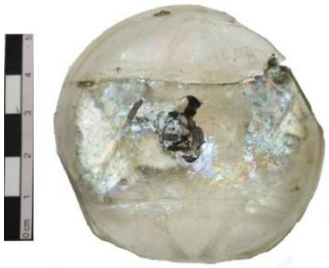
RAM 3847-06

RAM 3847-07 / P-1

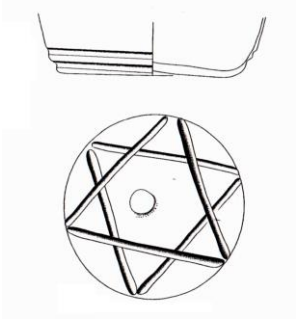


RAM 3847-07

RAM 3847-08 / P-1



RAM 3847-08



RAM 3847-08

Ramla, Ma'asiyaha Junction (A-4740)

RAM 4740-01 / N-3

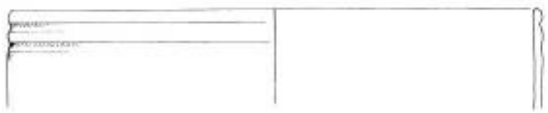
RAM 4740-01

RAM 4740-02 / P-3

RAM 4740-02

RAM 4740-03 / N-3

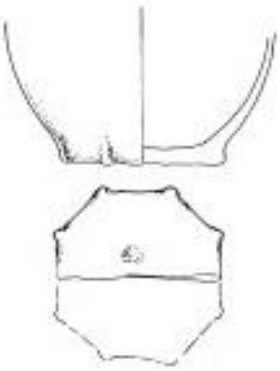
RAM 4740-04 / P-1



RAM 4740-03

RAM 4740-04

RAM 4740-05 / P-2a



RAM 4740-05

RAM 4740-06 / P-1

RAM 4740-06

RAM 4740-07 / N-1

RAM 4740-08 / P-1

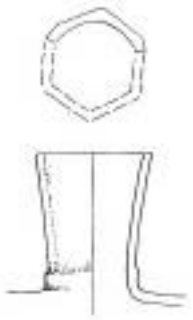
RAM 4740-09 / N-3

RAM 4740-09

RAM 4740-10 / P-1

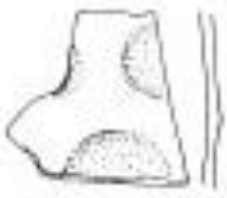
RAM 4740-11 / P-outlier

RAM 4740-12 / P-3



RAM 4740-12

RAM 4740-13 / P-3

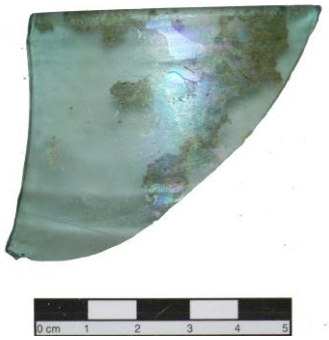


RAM 4740-13

Ramla, Lod-Na'an Railroad Track (A-4768)

RAM 4768-01 / N-3

RAM 4768-01



RAM 4768-02 / N-3

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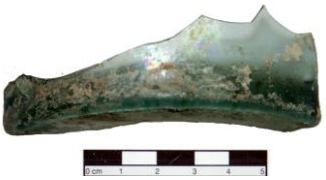

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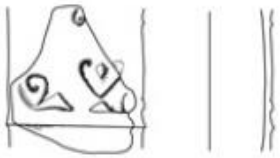
RAM 4768-03

RAM 4768-04 / P-1

RAM 4768-04

RAM 4768-05 / P-3



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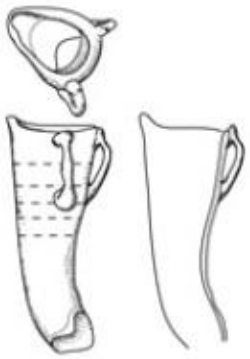
RAM 4768-06 / P-1



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RAM 4768-08 / P-4

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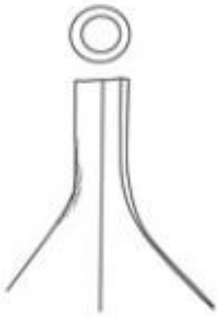
<tr><td> 
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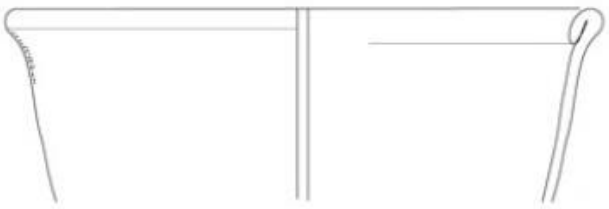
RAM 5947-01 / N-3</td><td colspan="2"> 
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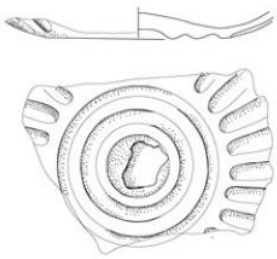
RAM 5947-02 / N-3</td><td> 
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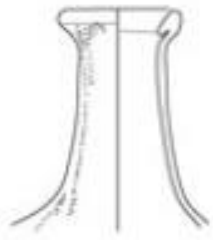

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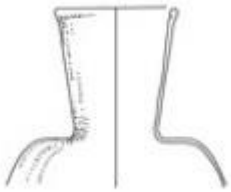

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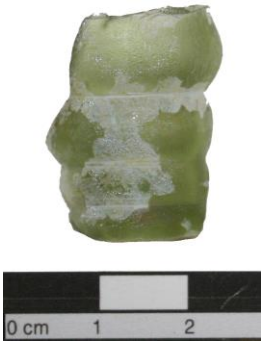

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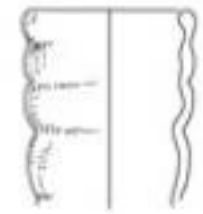

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RAM 5947-07 / N-3

RAM 5947-07

RAM 5947-08 / N-3

RAM 5947-08

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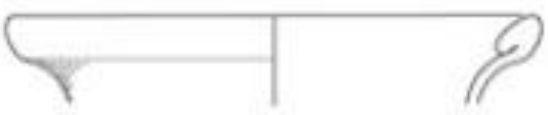

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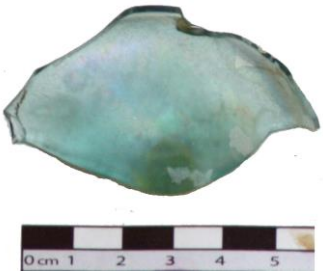
RAM 5947-10 / N-3

RAM 5947-10

RAM 5947-11 / N-3

RAM 5947-11



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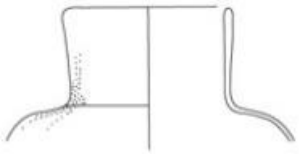

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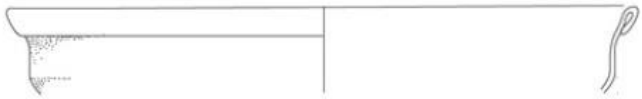

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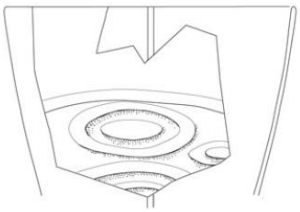

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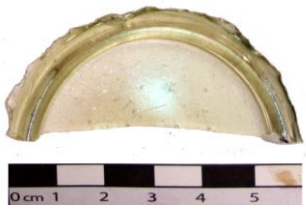
RAM 5947-16 / N-3

RAM 5947-16



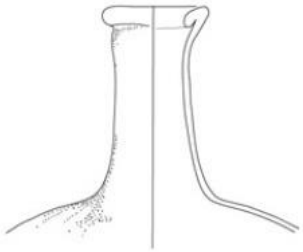
RAM 5947-17 / P-outlier

RAM 5947-17

RAM 5947-18 / N-3

RAM 5947-18

RAM 5947-19 / N-3



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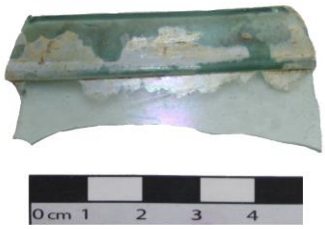
RAM 5947-20 / N-3



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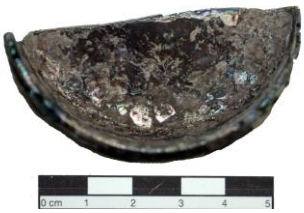
RAM 5947-22 / N-outlier

RAM 5947-23 / N-3

RAM 5947-24 / N-3

RAM 5947-25 / N-3



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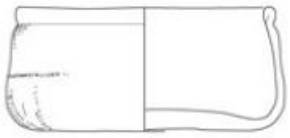
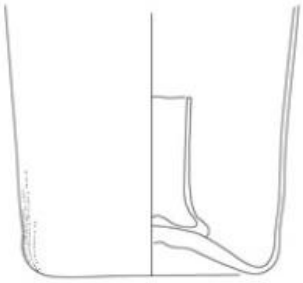


RAM 5947-26

RAM 5947-27 / P-1

RAM 5947-27

RAM 5947-28 / P-1



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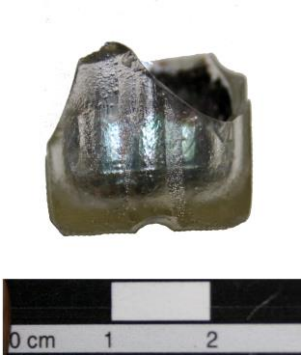

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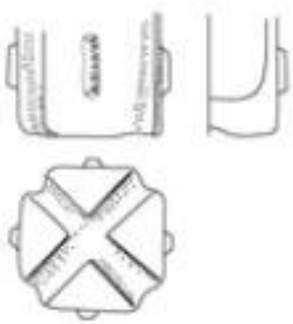
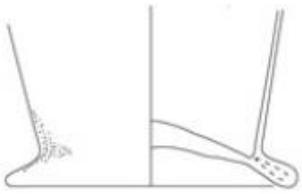


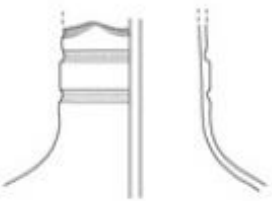
RAM 5947-29

RAM 5947-30 / P-1

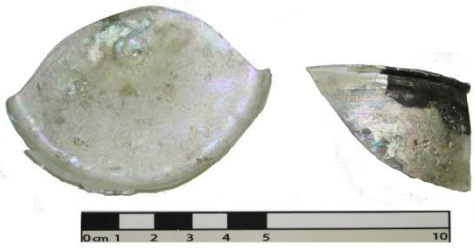


RAM 5947-30

RAM 5947-31 P-3



RAM 5947-31

Ramla, Ha-Etzel Street (A-6297)	
 RAM 6297-01 / P-1	 RAM 6297-01
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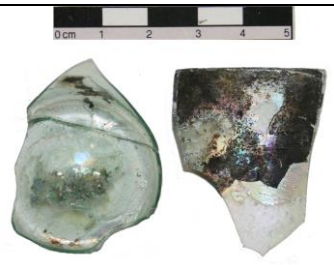 RAM 6297-03 / P-1	
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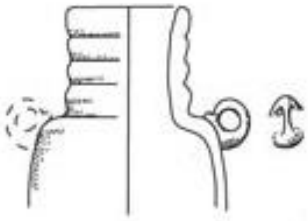 RAM 6297-04	
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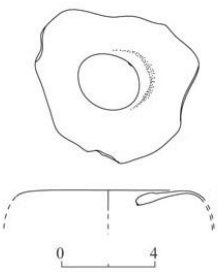
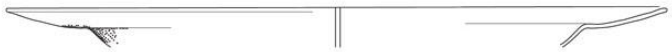
 RAM 6297-08	


RAM 6297-09 / P-1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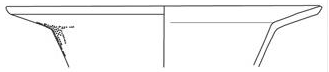
RAM 6297-10 / P-1


RAM 6297-10


RAM 6297-11 / P-1


RAM 6297-11


RAM 6297-12 / P-1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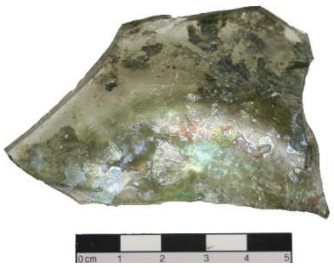
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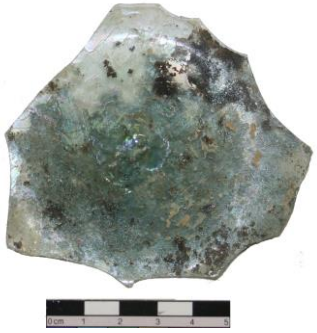
RAM 6297-13


RAM 6297-14 / P-1


RAM 6297-15 / P-1


RAM 6297-15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RAM 6297-16 / P-1

RAM 6297-16

Ramla, He-Hez Street (A-6490)

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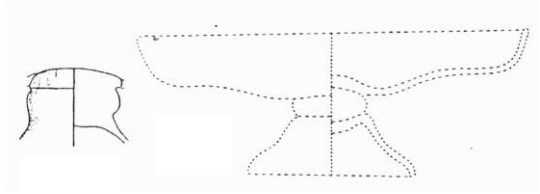

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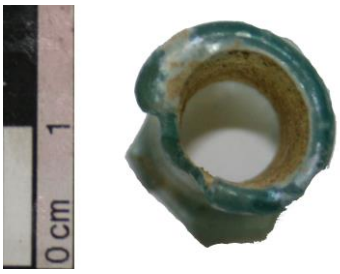
RAM 6490-02 / N-3

RAM 6490-03 / N-3

RAM 6490-04 / N-3



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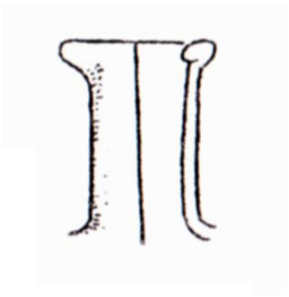

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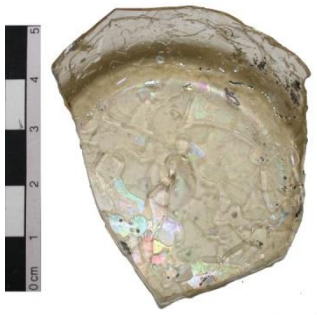

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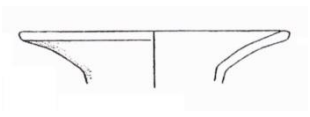
RAM 6490-05

RAM 6490-06 / P-1



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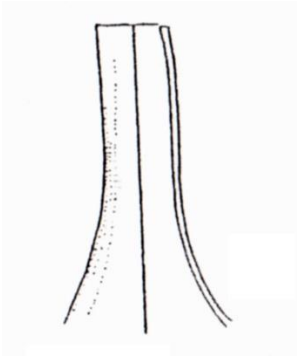
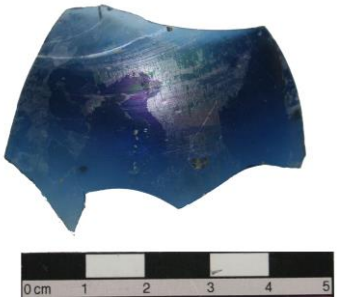
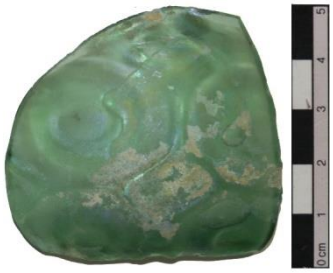
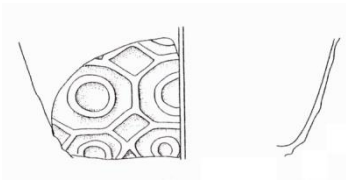
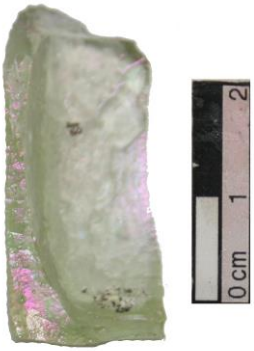
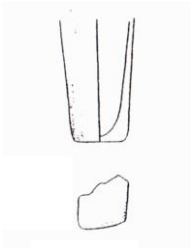
 RAM 6490-07 / P-4	 RAM 6490-07	 RAM 6490-08 / P-4
 RAM 6490-09 / P-4	 RAM 6490-10 / N-3	 RAM 6490-10
 RAM 6490-11 / P-3	 RAM 6490-11	 RAM 6490-12 / N/A
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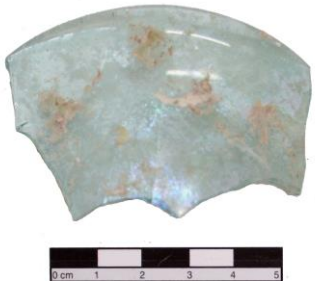 SEP 3791-02 / N-1	 SEP 3791-02	 SEP 3791-03 / N-1

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 SEP 3791-05 / N-1	 SEP 3791-05	 SEP 3791-06 / N-1
 SEP 3791-06	 SEP 3791-07 / N-1	 SEP 3791-07
 SEP 3791-08 / N-1	 SEP 3791-08	 SEP 3791-09 / N-1

SEP 3791-09

SEP 3791-10 / N-1

SEP 3791-10

SEP 3791-11 / N-1

SEP 3791-11

SEP 3791-12 / N-1

SEP 3791-12

SEP 3791-13 / P-1

SEP 3791-13

SEP 3791-14 / P-3

SEP 3791-14

SEP 3791-15 / P-1

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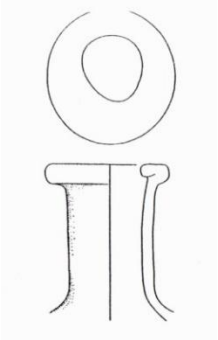
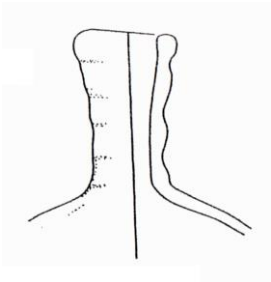
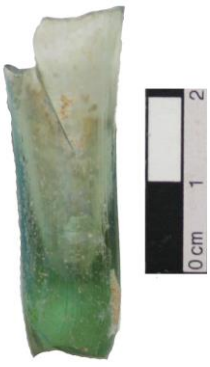
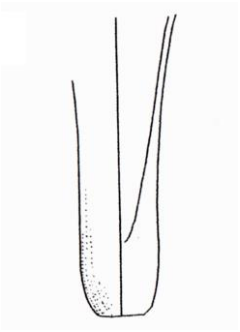
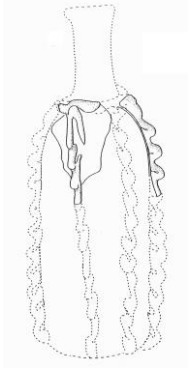
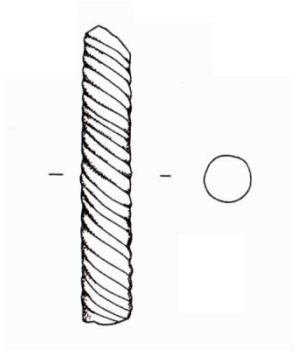
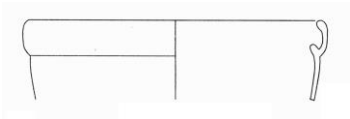
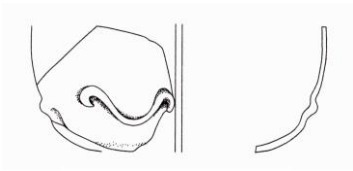
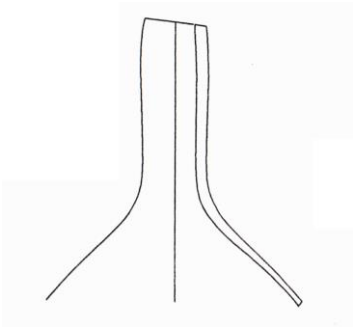
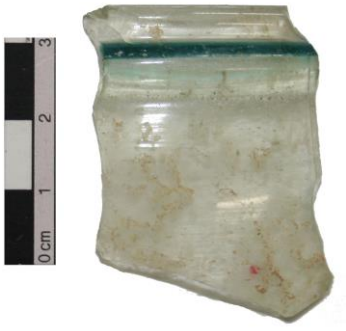
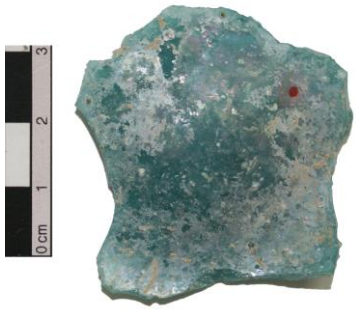
Tel Rosh (A-6055)		
 TR 6055-01 / N-1	 TR 6055-01	 TR 6055-02 / P-outlier
 TR 6055-02	 TR 6055-03 / N-1	 TR 6055-03
 TR 6055-04 / N-2	 TR 6055-04	

Tiberias, Roman Theatre (A-5583)		
 TIB 5583-01 / N-4	 TIB 5583-02 / N-1	 TIB 5583-02
 TIB 5583-03 / N-1	 TIB 5583-03	 TIB 5583-04 / N-1
 TIB 5583-04	 TIB 5583-05 / N-1	 TIB 5583-06 / N-3 Co
 TIB 5583-07 / P-4	 TIB 5583-07	 TIB 5583-08 / P-1

TIB 5583-09 / P-1



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TIB 5583-11 / P-1

TIB 5583-12 / P-1

TIB 5583-13 / P-1

TIB 5583-14 / P-2a

TIB 5583-15 / P-1

TIB 5583-15

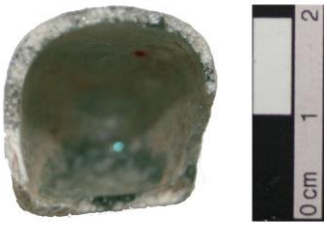
TIB 5583-16 / P-1

TIB 5583-17 / P-1

TIB 5583-18 / P-1

TIB 5583-19 / P-1

TIB 5583-20 / P-2a



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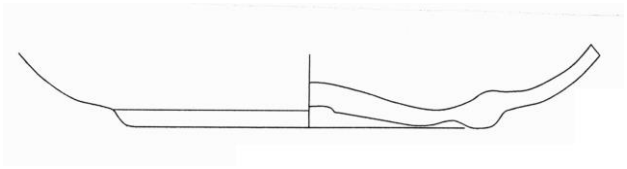
TIB 5583-22 / P-1

TIB 5583-22

TIB 5583-23 / P-1

TIB 5583-24 / P-1



TIB 5583-24

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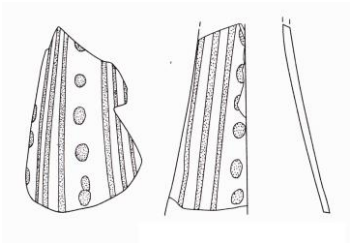
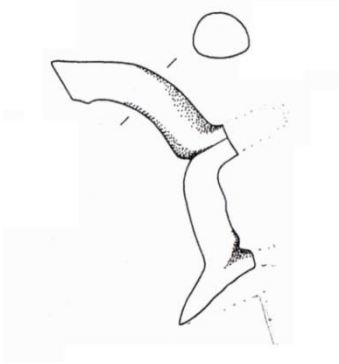
TIB 5583-26 / P-1

TIB 5583-27 / P-1

 TIB 5583-27	 TIB 5583-28 / P-1	 TIB 5583-28
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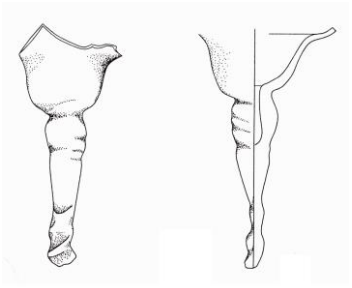 TIB 5583-30	 TIB 5583-30	

Appendix E: EPMA Data

E.1. EPMA analysis of the samples from Campaign 1. EPMA analysis was carried out at the Institute of Archaeology Wolfson Science Laboratory by Kevin Reeve. Each result is an average of 7 readings. The data is normalised. Note that sample AH 3746-06 (highlighted in red) has greatly increased error due to a mistake in sampling preparation. Samples are arranged in order of analysis. Data is as wt %. bdl = below detection limit, which is taken at values <0.01. Columns removed for being bdl = V_2O_5, NiO and Sb_2O_5.

Sepphoris	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	CoO	CuO	ZnO	SrO	SnO_2	BaO	PbO
SEP 3791 01	15.68	0.48	3.07	69.79	0.11	0.18	0.81	0.69	8.62	0.05	bdl	0.02	0.31	bdl	bdl	0.01	0.12	0.01	0.02	bdl
SEP 3791 02	14.21	0.55	3.20	71.56	0.10	0.05	0.79	0.55	8.34	0.06	bdl	0.02	0.40	0.01	bdl	0.01	0.09	0.01	0.03	0.01
SEP 3791 03	14.47	0.51	2.90	71.53	0.09	0.19	0.82	0.64	8.27	0.05	bdl	0.03	0.30	bdl	bdl	0.02	0.11	0.01	0.03	0.02
SEP 3791 04	15.26	0.50	3.16	70.61	0.10	0.13	0.87	0.75	7.98	0.06	bdl	0.02	0.34	bdl	0.01	bdl	0.15	0.01	0.03	0.01
SEP 3791 05 blue	14.94	0.54	2.78	67.94	0.07	0.16	0.88	0.85	7.12	0.06	bdl	0.01	0.74	0.01	2.85	0.09	0.10	0.22	0.03	0.61
SEP 3791 05 white	16.30	0.57	3.05	69.66	0.12	0.14	0.85	0.86	7.58	0.08	bdl	0.02	0.59	bdl	0.01	0.01	0.11	bdl	0.02	bdl
SEP 3791 06	15.55	0.56	3.17	69.65	0.12	0.08	0.89	0.72	8.58	0.06	bdl	0.02	0.41	bdl	0.01	bdl	0.11	bdl	0.03	0.02
SEP 3791 07	16.25	0.52	3.15	66.59	0.20	0.20	0.58	0.84	10.91	0.07	bdl	0.02	0.47	bdl	bdl	0.01	0.13	bdl	0.02	0.02
SEP 3791 08	14.08	0.61	3.27	69.42	0.11	0.11	0.76	0.64	10.24	0.07	bdl	0.02	0.44	bdl	0.01	bdl	0.13	bdl	0.02	bdl
SEP 3791 09	15.09	0.56	3.11	69.83	0.18	0.09	0.83	0.70	8.91	0.07	bdl	0.01	0.42	bdl	bdl	0.01	0.12	bdl	0.02	bdl
SEP 3791 10	14.05	0.62	3.30	69.61	0.10	0.11	0.75	0.64	10.13	0.07	bdl	0.02	0.41	bdl	0.01	bdl	0.09	0.01	0.04	bdl
SEP 3791 11	15.31	0.64	3.02	71.01	0.08	0.12	0.90	0.61	7.70	0.06	bdl	0.01	0.34	0.01	bdl	bdl	0.14	bdl	0.02	bdl
SEP 3791 12	14.77	0.55	3.31	71.89	0.05	0.10	0.78	0.55	7.31	0.08	bdl	0.02	0.42	bdl	bdl	bdl	0.11	bdl	0.04	bdl
SEP 3791 13	12.46	3.50	1.99	64.99	0.33	0.15	0.49	2.46	12.03	0.09	bdl	0.73	0.52	bdl	bdl	0.02	0.15	bdl	0.03	0.02
SEP 3791 14	15.66	6.17	1.47	67.61	0.09	0.33	0.50	2.01	4.55	0.06	bdl	1.00	0.36	bdl	bdl	bdl	0.11	bdl	0.03	bdl
SEP 3791 15	11.66	3.34	1.59	69.17	0.26	0.18	0.69	2.37	9.63	0.05	bdl	0.52	0.30	bdl	0.02	0.01	0.16	bdl	0.03	bdl
SEP 3791 16	13.01	3.13	0.97	67.64	0.38	0.12	0.57	2.46	10.99	0.08	bdl	0.04	0.38	0.01	0.02	0.01	0.13	bdl	0.03	bdl
Bet Shean	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Cr_2O_3	MnO	FeO	CoO	CuO	ZnO	SrO	SnO_2	BaO	PbO
BSH 2885 01	13.18	3.69	1.77	65.43	0.33	0.27	0.67	3.30	9.80	0.07	bdl	0.86	0.41	bdl	0.02	0.02	0.12	bdl	0.02	0.01

BSH 2885 02	10.75	2.95	1.65	71.35	0.23	0.23	0.64	2.27	8.67	0.06	bdl	0.69	0.30	bdl	bdl	0.02	0.14	bdl	0.03	bdl
BSH 2885 03	14.77	3.52	0.91	66.57	0.31	0.20	0.74	2.12	10.16	0.07	bdl	0.07	0.36	bdl	0.01	bdl	0.13	bdl	0.01	bdl
BSH 2885 04	12.00	3.35	1.64	68.53	0.28	0.25	0.64	2.66	9.44	0.06	bdl	0.62	0.33	bdl	bdl	0.01	0.15	bdl	0.02	bdl
BSH 2885 05	10.20	3.50	1.08	69.57	0.31	0.19	0.70	2.19	10.47	0.11	bdl	1.00	0.40	0.01	0.02	0.01	0.14	bdl	0.07	bdl
BSH 2885 06	14.09	0.62	2.98	70.43	0.17	0.06	0.79	0.91	9.16	0.08	0.01	0.03	0.42	bdl	0.01	0.01	0.16	bdl	0.03	bdl
BSH 2885 07	11.59	3.27	1.04	70.85	0.39	0.18	0.73	2.49	8.12	0.10	bdl	0.64	0.42	0.01	0.02	bdl	0.09	bdl	0.02	bdl
BSH 2885 08	13.14	3.82	0.83	68.67	0.25	0.18	0.59	1.85	9.55	0.09	bdl	0.42	0.37	0.01	bdl	0.03	0.14	bdl	0.04	bdl
BSH 2885 09	12.01	3.58	0.67	69.91	0.40	0.05	0.73	3.70	8.37	0.08	bdl	0.02	0.32	bdl	bdl	bdl	0.11	bdl	bdl	bdl
BSH 2885 10	12.12	3.10	0.56	70.45	0.35	0.13	0.72	3.29	8.42	0.08	bdl	0.31	0.25	bdl	0.01	0.01	0.14	bdl	0.02	bdl
BSH 2885 11	13.20	3.85	0.85	68.65	0.27	0.19	0.58	1.86	9.44	0.10	bdl	0.43	0.35	bdl	0.02	0.02	0.14	bdl	0.02	bdl
BSH 2885 12	10.48	3.12	1.08	70.94	0.33	0.18	0.68	2.63	8.90	0.12	bdl	0.85	0.44	bdl	0.04	0.02	0.11	bdl	0.06	bdl
Ramla	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**FeO**	**CoO**	**CuO**	**ZnO**	**SrO**	**SnO_2**	**BaO**	**PbO**
RAM 5947 01	15.18	0.43	2.71	67.07	0.06	0.13	1.08	0.26	11.91	0.20	bdl	0.02	0.74	0.01	bdl	bdl	0.13	bdl	0.02	0.01
RAM 5947 02	13.81	0.51	2.67	70.43	0.09	0.05	1.07	0.25	9.84	0.25	bdl	0.02	0.84	bdl	0.01	bdl	0.11	bdl	0.02	bdl
RAM 5947 03	15.31	0.57	3.44	70.22	0.10	0.11	0.87	0.39	7.73	0.16	bdl	0.06	0.79	bdl	0.01	0.01	0.13	bdl	0.02	bdl
RAM 5947 04	15.07	0.41	2.44	71.61	0.06	0.11	0.91	0.22	7.82	0.25	bdl	0.07	0.85	bdl	0.01	0.02	0.10	0.01	0.02	bdl
RAM 5947 05	15.27	0.43	2.36	69.54	0.07	0.17	1.00	0.25	9.74	0.22	bdl	0.01	0.76	bdl	0.02	bdl	0.10	bdl	0.02	bdl
RAM 5947 06	16.40	0.59	2.73	68.00	0.12	0.08	0.79	0.46	9.51	0.20	bdl	0.08	0.78	bdl	bdl	0.02	0.07	bdl	0.03	0.12
RAM 5947 07	14.93	0.48	2.52	69.77	0.07	0.07	1.05	0.25	9.63	0.24	bdl	0.02	0.82	0.01	bdl	bdl	0.07	bdl	0.03	bdl
RAM 5947 08	14.98	0.48	2.59	69.29	0.07	0.12	1.06	0.27	9.86	0.25	bdl	0.02	0.86	bdl	0.01	bdl	0.09	bdl	0.02	bdl
RAM 5947 09	12.56	0.64	3.45	74.11	0.05	0.06	0.65	0.45	7.40	0.06	bdl	0.01	0.39	bdl	0.01	bdl	0.10	bdl	0.02	bdl
RAM 5947 10	15.04	0.53	2.61	69.57	0.08	0.08	1.02	0.43	9.47	0.22	bdl	0.02	0.79	bdl	0.01	0.02	0.07	bdl	0.03	bdl
RAM 5947 11	15.21	0.47	2.66	69.40	0.08	0.22	0.91	0.34	9.47	0.24	bdl	0.02	0.83	bdl	bdl	bdl	0.09	bdl	0.02	0.01
RAM 5947 12	14.14	0.34	2.39	68.99	0.07	0.21	0.88	0.27	11.72	0.16	bdl	0.01	0.63	0.01	bdl	0.02	0.08	bdl	0.01	0.01
RAM 5947 13	14.19	0.55	2.57	69.82	0.08	0.09	1.08	0.23	10.02	0.28	bdl	0.02	0.88	bdl	bdl	0.02	0.10	bdl	0.02	bdl
RAM 5947 14	14.80	0.45	3.42	72.71	0.04	0.13	0.69	0.54	6.54	0.08	bdl	0.02	0.44	bdl	bdl	bdl	0.08	bdl	0.01	bdl
RAM 5947 15	14.53	0.46	2.67	70.41	0.07	0.11	1.05	0.25	9.18	0.24	bdl	0.02	0.84	bdl	bdl	bdl	0.11	bdl	0.02	0.01
RAM 5947 16	14.18	0.47	2.57	70.66	0.09	0.14	0.95	0.28	9.42	0.24	bdl	0.01	0.81	bdl	bdl	0.02	0.12	bdl	0.03	bdl

RAM 5947 17	14.37	4.54	1.83	68.28	0.19	0.23	0.57	2.94	4.78	0.08	bdl	1.45	0.52	bdl	bdl	0.02	0.12	bdl	0.05	bdl
RAM 5947 18	13.75	0.52	2.68	70.25	0.09	0.05	1.10	0.24	10.05	0.26	bdl	0.02	0.87	bdl	bdl	bdl	0.06	bdl	0.02	bdl
RAM 5947 19	13.94	0.49	2.72	70.55	0.08	0.07	1.01	0.26	9.69	0.23	bdl	0.02	0.79	bdl	bdl	0.02	0.07	bdl	0.02	0.01
RAM 5947 20	13.84	1.65	2.07	68.92	0.22	0.07	0.79	1.25	10.02	0.17	bdl	0.11	0.68	bdl	0.01	bdl	0.12	bdl	0.02	0.03
RAM 5947 21	16.15	0.50	2.41	68.30	0.10	0.24	1.01	0.43	9.66	0.25	bdl	0.02	0.78	bdl	0.01	0.01	0.10	bdl	0.02	bdl
RAM 5947 22	16.19	0.64	2.87	67.44	0.14	0.10	0.85	0.56	9.35	0.17	bdl	0.19	0.79	bdl	0.08	0.02	0.07	0.05	0.03	0.43
RAM 5947 23	14.77	0.46	2.68	70.13	0.07	0.13	1.06	0.26	9.20	0.24	bdl	0.01	0.83	bdl	bdl	0.01	0.09	bdl	0.02	bdl
RAM 5947 24	15.10	0.31	1.92	70.55	0.05	0.12	1.03	0.22	9.81	0.15	bdl	0.02	0.55	bdl	bdl	0.02	0.09	bdl	bdl	bdl
RAM 5947 25	14.73	0.46	2.70	69.89	0.08	0.09	0.97	0.26	9.51	0.25	bdl	0.03	0.89	bdl	bdl	0.01	0.09	0.01	0.02	bdl
RAM 5947 26	11.86	2.89	2.02	66.05	0.36	0.19	0.55	2.03	11.64	0.08	bdl	1.56	0.54	bdl	0.02	bdl	0.12	bdl	0.04	bdl
RAM 5947 27	11.59	3.12	1.63	69.63	0.27	0.23	0.65	2.23	9.45	0.05	bdl	0.72	0.29	bdl	bdl	0.02	0.08	bdl	0.02	bdl
RAM 5947 28	13.12	2.68	1.96	68.79	0.27	0.26	0.67	2.29	8.26	0.07	bdl	1.03	0.41	bdl	0.02	bdl	0.13	bdl	bdl	bdl
RAM 5947 29	11.65	4.89	1.05	72.36	0.07	0.28	0.51	2.18	6.21	0.03	bdl	0.35	0.24	bdl	bdl	0.01	0.11	bdl	0.01	bdl
RAM 5947 30	11.64	2.86	1.64	70.88	0.25	0.25	0.67	2.20	8.53	0.06	bdl	0.55	0.27	bdl	bdl	0.01	0.14	bdl	0.03	bdl
RAM 5947 31	12.10	5.20	1.02	70.35	0.12	0.28	0.54	2.58	6.85	0.03	bdl	0.48	0.22	bdl	bdl	0.03	0.19	bdl	0.00	0.01

Ahihud	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**FeO**	**CoO**	**CuO**	**ZnO**	**SrO**	**SnO_2**	**BaO**	**PbO**
AH 3746 01	13.01	0.38	3.11	73.28	0.10	0.07	0.74	0.52	8.27	0.05	bdl	0.01	0.28	bdl	0.02	bdl	0.10	bdl	0.03	bdl
AH 3746 02	14.13	0.51	2.71	69.63	0.11	0.05	1.14	0.35	10.05	0.26	0.01	0.02	0.88	bdl	bdl	0.02	0.09	bdl	0.02	0.01
AH 3746 03	14.96	0.56	2.82	68.96	0.14	0.12	0.90	0.58	8.95	0.11	bdl	0.31	0.87	bdl	0.07	0.02	0.09	0.02	0.02	0.38
AH 3746 04	14.22	0.56	3.44	72.08	0.07	0.09	0.68	0.69	7.42	0.09	bdl	0.02	0.45	bdl	bdl	bdl	0.12	bdl	0.03	bdl
AH 3746 05	14.22	0.73	2.89	69.37	0.18	0.05	0.79	0.72	9.85	0.15	bdl	0.17	0.67	bdl	0.02	0.02	0.09	0.01	0.04	0.03
AH 3746 06	14.07	0.56	3.44	72.22	0.09	0.08	0.68	0.72	7.40	0.09	bdl	0.02	0.47	bdl	0.01	0.01	0.09	bdl	0.03	bdl
AH 3746 07	14.54	0.68	3.15	70.26	0.14	0.04	0.90	0.63	9.00	0.07	bdl	0.01	0.41	bdl	0.01	bdl	0.09	bdl	0.03	bdl
AH 3746 08	13.85	0.45	3.39	72.22	0.10	0.05	0.64	0.73	7.99	0.06	bdl	0.02	0.32	bdl	bdl	0.02	0.12	bdl	0.03	bdl
AH 3746 09	14.18	0.76	2.90	69.38	0.18	0.04	0.76	0.71	9.86	0.16	bdl	0.17	0.70	bdl	0.02	0.01	0.08	0.01	0.02	0.04
AH 3746 10	18.04	0.84	4.47	70.01	0.06	0.14	0.95	0.47	2.64	0.51	bdl	0.04	1.66	bdl	0.02	0.01	0.08	bdl	0.03	bdl
AH 3746 11	15.08	0.57	2.57	68.67	0.10	0.10	1.00	0.41	9.87	0.25	0.01	0.31	0.89	0.01	0.02	0.02	0.08	bdl	0.01	0.02
AH 3746 12	11.95	0.43	3.11	71.12	0.14	0.03	0.67	0.41	11.47	0.07	bdl	0.01	0.36	bdl	0.01	0.01	0.14	bdl	0.04	bdl

AH 3746 13	12.59	0.43	3.45	73.27	0.11	0.08	0.68	0.61	8.12	0.06	bdl	0.02	0.40	bdl	0.01	0.01	0.11	0.01	0.03	bdl
Ramla	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**FeO**	**CoO**	**CuO**	**ZnO**	**SrO**	**SnO_2**	**BaO**	**PbO**
RAM 4768 01	14.74	0.49	2.52	69.61	0.07	0.08	1.09	0.25	9.89	0.25	bdl	0.01	0.82	bdl	0.01	bdl	0.10	bdl	0.02	bdl
RAM 4768 02	14.67	0.50	2.54	69.62	0.08	0.08	1.10	0.26	9.90	0.26	bdl	0.02	0.80	0.01	0.01	0.01	0.11	bdl	0.02	bdl
RAM 4768 03	14.70	0.55	2.42	69.27	0.10	0.05	1.09	0.34	10.26	0.26	bdl	0.02	0.81	bdl	bdl	0.01	0.07	bdl	0.03	bdl
RAM 4768 04	14.01	3.53	1.91	65.43	0.28	0.28	0.69	2.71	9.78	0.06	bdl	0.79	0.34	bdl	bdl	0.01	0.11	bdl	0.03	bdl
RAM 4768 05	11.59	4.99	1.00	71.83	0.10	0.26	0.59	2.40	6.36	0.03	bdl	0.47	0.20	bdl	0.01	bdl	0.13	bdl	0.02	0.01
RAM 4768 06	14.43	2.82	1.83	66.62	0.27	0.19	0.73	2.10	9.28	0.08	bdl	1.05	0.41	bdl	bdl	0.01	0.11	bdl	0.02	0.01
RAM 4768 07	14.09	0.47	2.59	70.35	0.06	0.02	1.18	0.22	9.78	0.23	bdl	0.02	0.80	bdl	bdl	0.02	0.11	bdl	0.02	bdl
RAM 4768 08	14.32	2.83	2.45	67.09	0.19	0.10	0.70	2.23	6.69	0.13	0.01	1.14	1.63	0.07	0.24	0.06	0.08	bdl	0.01	0.01
RAM 4768 09	13.18	2.60	2.25	67.76	0.26	0.14	0.73	1.75	8.68	0.14	bdl	0.78	1.26	0.05	0.19	0.04	0.08	bdl	0.04	0.03
RAM 4768 10	12.62	4.34	0.92	70.78	0.09	0.32	0.55	2.86	6.65	0.04	bdl	0.40	0.22	bdl	bdl	bdl	0.14	0.01	bdl	bdl
RAM 4768 11	14.03	2.79	1.82	68.54	0.26	0.22	0.77	2.66	7.41	0.07	0.01	0.90	0.36	bdl	0.01	0.02	0.10	bdl	0.02	bdl
Ramla	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Cr_2O_3**	**MnO**	**FeO**	**CoO**	**CuO**	**ZnO**	**SrO**	**SnO_2**	**BaO**	**PbO**
RAM 4740 01	13.04	0.66	2.71	70.97	0.10	0.06	1.05	0.36	9.77	0.27	bdl	0.02	0.86	bdl	0.02	0.01	0.08	bdl	0.01	bdl
RAM 4740 02	11.49	4.96	1.06	72.13	0.06	0.35	0.46	2.17	6.54	0.03	bdl	0.35	0.23	bdl	0.01	0.01	0.12	bdl	0.02	bdl
RAM 4740 03	13.69	0.83	2.88	69.50	0.13	0.06	0.87	0.35	10.21	0.30	bdl	0.03	1.04	bdl	0.02	0.01	0.06	bdl	0.02	bdl
RAM 4740 04	13.89	2.82	1.84	66.76	0.30	0.25	0.64	2.20	9.71	0.06	bdl	1.01	0.29	bdl	bdl	0.01	0.14	bdl	0.04	bdl
RAM 4740 05	13.77	3.09	0.96	67.46	0.40	0.15	0.82	2.64	8.87	0.07	bdl	1.23	0.34	bdl	0.01	bdl	0.14	bdl	0.01	bdl
RAM 4740 06	12.91	2.70	1.78	68.45	0.33	0.22	0.73	2.54	8.67	0.08	bdl	0.91	0.45	bdl	bdl	0.01	0.14	bdl	0.04	0.01
RAM 4740 07	14.57	0.56	3.34	69.38	0.10	0.14	0.73	0.71	9.73	0.09	bdl	0.03	0.43	bdl	0.01	0.01	0.11	bdl	0.03	bdl
RAM 4740 08	10.09	2.94	1.78	69.31	0.31	0.23	0.57	2.31	10.93	0.07	bdl	0.86	0.41	bdl	0.01	0.01	0.13	bdl	0.03	bdl
RAM 4740 09	14.95	0.46	2.18	68.58	0.06	0.12	1.19	0.26	11.05	0.24	bdl	0.02	0.74	bdl	0.01	0.02	0.08	bdl	0.01	bdl
RAM 4740 10	10.15	2.94	1.78	69.27	0.30	0.22	0.56	2.34	10.93	0.08	bdl	0.82	0.40	bdl	0.01	0.01	0.12	bdl	0.04	0.01
RAM 4740 11	13.43	1.99	1.93	68.97	0.24	0.05	0.63	1.61	9.95	0.15	bdl	0.10	0.66	bdl	0.02	0.02	0.13	bdl	0.01	0.09
RAM 4740 12	13.82	4.93	1.12	69.81	0.09	0.31	0.59	2.20	6.35	0.04	bdl	0.26	0.31	bdl	bdl	bdl	0.11	bdl	0.02	bdl
RAM 4740 13	11.45	5.19	1.05	71.67	0.08	0.36	0.48	2.04	6.79	0.04	bdl	0.40	0.26	bdl	bdl	bdl	0.12	bdl	0.01	bdl

Table E.2. EPMA analysis of Corning A. Each value is a single area (and not an average of points). Data was taken at the start, mid-point and end of the session.

Start	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	V_2O_3	Cr_2O_3	MnO	FeO	CoO	NiO	CuO	ZnO	SrO	SnO_2	Sb_2O_5	BaO	PbO
1	14.48	2.50	0.98	66.92	0.15	0.17	0.09	2.92	5.11	0.67	0.01	bdl	1.04	0.91	0.18	0.02	1.25	0.07	0.15	0.23	1.70	0.44	0.06
2	14.65	2.55	0.98	66.79	0.08	0.14	0.09	2.95	5.10	0.72	bdl	bdl	1.00	0.92	0.17	bdl	1.24	0.04	0.14	0.22	1.67	0.46	0.10
3	14.53	2.59	0.98	66.62	0.11	0.14	0.09	2.99	5.12	0.71	0.02	0.01	1.05	1.00	0.19	0.02	1.18	0.06	0.22	0.20	1.68	0.43	0.07
4	14.50	2.51	0.96	66.77	0.12	0.17	0.09	2.95	5.16	0.71	0.01	0.01	1.05	1.01	0.15	0.04	1.21	0.02	0.18	0.19	1.69	0.46	0.06
5	14.56	2.56	0.98	66.91	0.15	0.13	0.09	2.83	5.03	0.74	0.02	0.02	1.07	0.99	0.16	0.03	1.18	0.05	0.07	0.18	1.75	0.45	0.08
6	14.59	2.57	0.95	67.07	0.14	0.18	0.08	2.96	5.07	0.70	0.01	0.01	0.99	0.92	0.19	0.02	1.22	0.00	0.08	0.15	1.64	0.43	0.04
7	14.52	2.57	0.98	66.88	0.10	0.17	0.09	2.99	5.12	0.72	0.02	bdl	1.03	0.90	0.16	0.02	1.19	0.04	0.17	0.21	1.63	0.47	0.05
Mid-Session																							
349	14.36	2.56	0.99	66.90	0.10	0.14	0.09	2.97	5.12	0.71	0.01	bdl	1.04	0.93	0.17	0.03	1.22	0.04	0.23	0.17	1.68	0.50	0.07
463	14.57	2.58	0.98	66.81	0.14	0.17	0.09	2.91	5.22	0.68	0.01	bdl	1.03	0.91	0.17	0.02	1.22	0.04	0.17	0.21	1.56	0.46	0.07
554	14.42	2.55	0.98	66.90	0.14	0.18	0.10	2.95	5.13	0.72	bdl	bdl	1.00	0.94	0.15	0.05	1.20	0.01	0.17	0.17	1.65	0.49	0.10
End																							
723	14.61	2.63	0.98	66.82	0.09	0.16	0.09	2.91	5.16	0.71	0.01	bdl	0.98	0.90	0.19	bdl	1.20	0.07	0.09	0.22	1.67	0.48	0.04
724	14.19	2.56	0.97	67.09	0.11	0.16	0.10	2.92	5.15	0.72	bdl	bdl	1.04	0.92	0.17	0.03	1.22	0.06	0.17	0.18	1.65	0.52	0.06
725	14.44	2.55	0.97	66.85	0.10	0.17	0.09	2.93	5.24	0.69	0.03	bdl	1.05	0.92	0.15	bdl	1.19	0.04	0.16	0.22	1.71	0.45	0.05

Appendix F: Comparison of Repeat Analysis from Campaign 2

F.1. A comparison of repeat analyses from selected samples from Campaign 2. The Relative Percentage Difference (R%D) between each pair and the Average R%D for all the results are given. Data as wt% for the major and minor oxides, and ppm for trace.

	Major and Minor Oxides in wt %										Trace elements in ppm						
Samples	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**
JER 5124 22 (1)	12.51	0.44	3.12	75.35	0.06	0.76	0.78	6.36	0.08	0.41	10.4	135.8	13.7	162.4	171	1.7	4.6
JER 5124 22 (2)	12.10	0.46	3.42	75.48	0.08	0.73	0.90	6.22	0.08	0.41	10.8	142.4	13.3	148.7	163	1.6	4.2
R%D	*3.30*	*-3.43*	*-9.76*	*-0.17*	*-46.90*	*4.02*	*-15.02*	*2.19*	*1.74*	*1.07*	*-3.25*	*-4.86*	*2.89*	*8.39*	*4.64*	*5.86*	*8.70*
NS 6362 01 (1)	11.33	0.59	3.28	75.18	0.07	0.76	0.53	7.60	0.08	0.46	9.4	181.1	15.8	25.2	175	1.8	5.1
NS 6362 01 (2)	11.32	0.59	3.27	75.09	0.07	0.78	0.53	7.68	0.08	0.45	9.3	183.9	15.5	27.0	175	1.8	4.7
R%D	*0.07*	*-0.38*	*0.15*	*0.13*	*-3.50*	*-2.73*	*0.40*	*-1.10*	*-0.29*	*0.12*	*0.72*	*-1.52*	*2.37*	*-7.20*	*0.27*	*1.22*	*8.38*
HB 3032 18 (1)	12.64	3.32	1.57	68.17	0.27	0.69	2.74	9.17	0.08	0.39	12.6	268.4	18.1	12.8	8262	3.8	6.9
HB 3032 18 (2)	12.71	3.35	1.58	67.99	0.27	0.69	2.75	9.23	0.08	0.40	12.9	269.5	17.8	13.5	8265	3.9	7.1
R%D	*-0.55*	*-0.81*	*-0.86*	*0.27*	*-1.34*	*0.47*	*-0.29*	*-0.63*	*-2.16*	*-0.66*	*-2.13*	*-0.41*	*1.46*	*-5.41*	*-0.04*	*-1.88*	*-1.85*
TIB 5583 16 (1)	13.00	2.54	1.81	67.99	0.32	1.01	3.06	8.76	0.09	0.47	13.3	280.5	20.3	16.3	8053	4.7	9.0
TIB 5583 16 (2)	12.99	2.57	1.82	67.91	0.32	1.01	3.03	8.84	0.09	0.47	12.2	280.4	20.3	16.8	7908	4.7	8.9
R%D	*0.09*	*-0.94*	*-1.10*	*0.12*	*0.81*	*0.38*	*0.98*	*-1.00*	*-0.67*	*-0.51*	*8.41*	*0.04*	*-0.07*	*-2.68*	*1.80*	*-1.03*	*1.53*
NS 6362 05 (1)	14.58	0.44	2.21	70.83	0.06	1.05	0.24	9.42	0.24	0.82	7.8	212.5	31.8	39.8	174	3.1	7.3
NS 6362 05 (2)	14.57	0.44	2.19	70.99	0.06	1.03	0.25	9.28	0.24	0.82	7.9	209.2	31.6	40.1	209	3.2	6.8
R%D	*0.07*	*0.73*	*0.51*	*-0.23*	*0.02*	*1.32*	*-5.27*	*1.44*	*0.65*	*0.13*	*-1.44*	*1.55*	*0.72*	*-0.70*	*-19.97*	*-2.51*	*7.40*
JER 5124 09 (1)	18.61	0.43	2.65	66.23	0.10	1.22	0.37	1.99	0.25	1.04	6.7	184.8	32.4	bdl	242	9.9	53.9
JER 5124 09 (2)	19.22	0.47	2.87	64.34	0.09	1.27	0.37	2.26	0.24	1.08	5.1	199.5	30.7	46.9	258	9.7	52.8
R%D	*-3.25*	*-7.71*	*-8.29*	*2.85*	*11.31*	*-4.15*	*0.44*	*-13.52*	*6.32*	*-3.82*	*23.39*	*-7.97*	*5.40*	*n/a*	*-6.69*	*2.28*	*2.03*
TIB 5583 01 (1)	17.69	0.86	4.42	70.13	0.05	0.99	0.43	2.82	0.53	1.90	4.4	262.2	76.2	101.8	458	7.4	14.4
TIB 5583 01 (2)	17.72	0.85	4.43	70.15	0.05	1.00	0.43	2.80	0.52	1.86	3.0	263.9	74.1	102.6	449	7.3	14.4
R%D	*-0.20*	*0.30*	*-0.18*	*-0.02*	*5.91*	*-0.94*	*-0.27*	*0.57*	*0.98*	*2.20*	*32.62*	*-0.66*	*2.78*	*-0.85*	*1.98*	*1.97*	*0.01*
Average R%D	**-0.07**	**-1.75**	**-2.79**	**0.42**	**-4.81**	**-0.23**	**-2.72**	**-1.72**	**0.94**	**-0.21**	**8.33**	**-1.98**	**2.22**	**-1.41**	**-2.57**	**0.84**	**3.74**

Trace elements in ppm

Samples	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd	In	SnO_2	Sb_2O_3
JER 5124 22 (1)	3.9	7.4	3.8	1.4	12.2	454.1	8.1	60.3	2.1	0.3	0.04	bdl	bdl	0.7	bdl
JER 5124 22 (2)	3.9	8.2	3.8	1.6	13.3	439.5	7.8	59.3	2.1	0.3	0.04	bdl	bdl	0.7	bdl
R%D	*-0.15*	*-10.49*	*-0.15*	*-11.06*	*-9.03*	*3.22*	*3.73*	*1.60*	*0.47*	*5.51*	*-0.34*	*n/a*	bdl	*-11.06*	bdl
NS 6362 01 (1)	3.9	9.0	4.5	1.8	10.2	459.7	8.3	53.6	2.0	0.6	0.03	0.008	bdl	0.9	0.44
NS 6362 01 (2)	4.1	9.4	4.4	1.8	10.2	459.7	8.3	53.4	2.0	0.6	0.04	0.034	bdl	0.9	0.99
R%D	*-3.67*	*-5.41*	*1.19*	*-0.04*	*-0.01*	*-0.01*	*-0.02*	*0.44*	*1.69*	*2.78*	*-7.68*	*-309.128*	bdl	*-1.81*	*-125.14*
HB 3032 18 (1)	59.2	31.2	2.7	2.8	17.8	513.1	7.3	46.2	1.8	2.7	0.13	0.032	bdl	2.0	bdl
HB 3032 18 (2)	58.3	30.9	2.7	2.6	18.2	519.9	7.5	46.7	1.8	2.9	1.69	0.020	bdl	2.2	bdl
R%D	*1.44*	*1.07*	*-0.72*	*4.62*	*-2.44*	*-1.33*	*-1.59*	*-1.13*	*-0.94*	*-7.26*	*-1218.87*	*36.865*	bdl	*-11.53*	bdl
TIB 5583 16 (1)	34.4	37.9	3.3	3.1	17.6	764.6	8.2	49.4	2.0	1.9	0.05	0.058	bdl	1.3	bdl
TIB 5583 16 (2)	113.9	37.3	3.3	3.1	17.7	775.0	8.1	50.0	2.0	1.9	1.08	0.048	bdl	1.4	bdl
R%D	*-231.61*	*1.56*	*-1.61*	*1.13*	*-0.34*	*-1.36*	*0.96*	*-1.17*	*-0.63*	*2.95*	*-2168.58*	*16.191*	bdl	*-5.16*	bdl
NS 6362 05 (1)	3.1	15.2	3.5	0.9	4.1	188.7	7.7	234.0	4.2	0.1	0.08	0.069	bdl	0.7	0.17
NS 6362 05 (2)	4.5	17.0	3.7	1.0	4.2	185.5	7.6	233.5	4.2	0.1	0.08	0.064	bdl	0.6	0.20
R%D	*-46.51*	*-11.98*	*-3.99*	*-11.96*	*-2.39*	*1.68*	*1.36*	*0.22*	*-0.44*	*-59.48*	*1.37*	*7.669*	bdl	*13.00*	*-14.78*
JER 5124 09 (1)	40687.4	3399.7	4.0	156.7	5.8	168.8	7.8	170.4	3.9	0.1	58.09	0.054	8.441	2783.4	228.58
JER 5124 09 (2)	40460.8	3091.3	4.3	117.1	5.7	163.2	7.4	159.1	3.5	0.1	62.06	0.097	9.467	3211.0	212.58
R%D	*0.56*	*9.07*	*-6.06*	*25.24*	*2.07*	*3.30*	*5.38*	*6.65*	*11.69*	*-43.07*	*-6.83*	*-78.917*	*-12.157*	*-15.36*	*7.00*
TIB 5583 01 (1)	4.2	31.8	6.6	0.1	9.3	217.8	11.3	250.3	6.2	0.1	0.10	0.054	bdl	1.0	bdl
TIB 5583 01 (2)	4.2	30.0	6.6	0.1	9.2	216.5	11.3	247.0	6.2	0.1	0.10	0.049	bdl	0.9	bdl
R%D	*1.73*	*5.72*	*-1.10*	*57.26*	*1.10*	*0.57*	*0.22*	*1.29*	*0.36*	*-27.41*	*3.17*	*8.995*	bdl	*14.89*	bdl
Average R%D	**-39.74**	**-1.49**	**-1.78**	**9.31**	**-1.58**	**0.87**	**1.43**	**1.13**	**1.74**	**-18.00**	**-485.39**	**n/a**	**-14.30**	**-2.43**	**n/a**

Trace elements in ppm

Samples	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3
JER 5124 22 (1)	0.09	249.0	8.1	15.6	1.8	6.8	1.3	0.4	1.0	0.2	1.2	0.3	0.6	0.1	0.6	0.1
JER 5124 22 (2)	0.09	239.2	7.7	15.0	1.7	6.5	1.3	0.4	1.0	0.2	1.1	0.2	0.6	0.1	0.6	0.1
R%D	*-2.02*	*3.91*	*4.89*	*3.52*	*3.58*	*4.81*	*-0.38*	*2.24*	*1.43*	*0.89*	*9.25*	*7.86*	*6.24*	*2.96*	*0.47*	*5.32*
NS 6362 01 (1)	0.15	262.7	7.7	14.8	1.8	6.8	1.4	0.4	1.2	0.2	1.1	0.2	0.7	0.1	0.6	0.1
NS 6362 01 (2)	0.15	258.6	7.5	14.7	1.8	7.0	1.4	0.5	1.3	0.2	1.1	0.2	0.6	0.1	0.6	0.1
R%D	*-0.03*	*1.56*	*3.27*	*0.82*	*2.64*	*-1.52*	*-0.40*	*-7.24*	*-3.04*	*-2.27*	*0.59*	*-1.05*	*1.71*	*13.84*	*3.79*	*6.27*
HB 3032 18 (1)	0.17	250.8	7.1	12.6	1.6	6.2	1.2	0.3	1.0	0.2	1.0	0.2	0.5	0.1	0.5	0.1
HB 3032 18 (2)	0.17	250.4	7.1	12.9	1.6	6.2	1.2	0.3	1.0	0.2	1.0	0.2	0.5	0.1	0.5	0.1
R%D	*-4.43*	*0.16*	*-0.17*	*-1.88*	*-0.69*	*1.00*	*1.58*	*-1.19*	*0.21*	*-4.06*	*1.69*	*1.01*	*-5.46*	*-2.92*	*0.80*	*-6.07*
TIB 5583 16 (1)	0.15	244.3	7.2	13.3	1.7	6.8	1.3	0.4	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1
TIB 5583 16 (2)	0.14	244.8	7.2	13.2	1.7	6.8	1.3	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.6	0.1
R%D	*8.31*	*-0.18*	*0.58*	*1.25*	*0.92*	*1.19*	*0.41*	*6.27*	*4.23*	*-7.51*	*2.54*	*-4.47*	*-1.32*	*9.89*	*6.96*	*4.00*
NS 6362 05 (1)	0.07	156.7	7.8	15.2	1.8	6.8	1.4	0.3	1.2	0.2	1.1	0.2	0.7	0.1	0.7	0.1
NS 6362 05 (2)	0.07	154.7	7.7	15.2	1.8	6.8	1.4	0.3	1.2	0.2	1.1	0.2	0.6	0.1	0.7	0.1
R%D	*-9.18*	*1.26*	*2.10*	*-0.04*	*2.78*	*0.26*	*-3.90*	*5.62*	*-1.73*	*-3.39*	*-6.33*	*-0.39*	*4.61*	*2.93*	*-0.11*	*-4.98*
JER 5124 09 (1)	bdl	173.0	8.5	16.8	1.9	7.1	1.5	0.4	1.1	0.2	1.2	0.2	0.7	0.1	0.7	0.1
JER 5124 09 (2)	bdl	173.6	7.3	14.5	1.8	7.5	1.6	0.4	1.3	0.2	1.3	0.2	0.7	0.1	0.7	0.1
R%D	bdl	*-0.36*	*13.58*	*14.09*	*6.83*	*-6.40*	*-9.13*	*8.18*	*-17.04*	*1.49*	*-5.82*	*0.08*	*-5.21*	*0.61*	*-4.41*	*1.12*
TIB 5583 01 (1)	bdl	238.1	10.6	22.0	2.6	11.1	2.3	0.6	2.0	0.3	1.9	0.4	1.1	0.2	1.1	0.2
TIB 5583 01 (2)	bdl	236.3	10.6	21.5	2.6	11.1	2.4	0.6	1.9	0.3	1.8	0.4	1.1	0.2	1.1	0.2
R%D	bdl	*0.76*	*0.19*	*2.07*	*0.75*	*0.01*	*-2.23*	*4.30*	*4.25*	*-0.12*	*5.11*	*0.17*	*-0.57*	*8.66*	*-1.23*	*-0.17*
Average R%D	**0.26**	**1.02**	**3.49**	**2.83**	**2.40**	**-0.09**	**-2.01**	**2.60**	**-1.67**	**-2.14**	**1.01**	**0.46**	**-0.001**	**5.14**	**0.90**	**0.78**

	Trace elements in ppm								
Samples	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
JER 5124 22 (1)	1.2	0.1	0.06	bdl	bdl	6	bdl	1.0	0.6
JER 5124 22 (2)	1.2	0.1	0.07	bdl	bdl	6	bdl	0.9	0.6
R%D	*-0.21*	*7.15*	*-5.28*	bdl	bdl	*1.42*	bdl	*5.28*	*1.04*
NS 6362 01 (1)	1.2	0.1	0.07	bdl	bdl	13	bdl	0.9	0.8
NS 6362 01 (2)	1.2	0.1	0.06	bdl	bdl	13	bdl	1.0	0.8
R%D	*0.20*	*6.36*	*3.18*	bdl	bdl	*-7.15*	bdl	*-1.18*	*-1.45*
HB 3032 18 (1)	1.0	0.1	0.13	bdl	bdl	9	bdl	0.9	0.4
HB 3032 18 (2)	0.9	0.1	0.14	bdl	bdl	8	bdl	0.9	0.4
R%D	*4.41*	*-7.22*	*-2.99*	bdl	bdl	*10.19*	bdl	*-3.52*	*-0.51*
TIB 5583 16 (1)	1.1	0.1	0.09	bdl	bdl	13	bdl	0.9	0.5
TIB 5583 16 (2)	1.1	0.1	0.08	bdl	bdl	13	bdl	0.9	0.5
R%D	*-5.98*	*5.18*	*9.04*	bdl	bdl	*3.22*	bdl	*2.19*	*1.14*
NS 6362 05 (1)	4.4	0.2	0.06	bdl	bdl	2	bdl	1.7	1.3
NS 6362 05 (2)	4.5	0.2	0.06	bdl	bdl	2	bdl	1.6	1.3
R%D	*-1.13*	*2.81*	*3.50*	bdl	bdl	*-11.06*	bdl	*2.27*	*1.93*
JER 5124 09 (1)	3.2	0.2	0.75	bdl	1.17	22484	7.95	1.5	1.2
JER 5124 09 (2)	3.3	0.2	0.52	bdl	1.05	29609	8.11	1.4	1.2
R%D	*-3.11*	*6.40*	*31.08*	bdl	*10.12*	*-31.69*	*-1.98*	*7.77*	*2.64*
TIB 5583 01 (1)	5.1	0.3	0.08	bdl	bdl	4	bdl	2.1	1.5
TIB 5583 01 (2)	5.0	0.3	0.07	bdl	bdl	5	bdl	2.1	1.5
R%D	*1.25*	*3.44*	*14.69*	bdl	bdl	*-20.10*	bdl	*0.17*	*-0.96*
Average R%D	**-0.65**	**3.44**	**7.60**	**n/a**	**n/a**	**-7.88**	**n/a**	**1.86**	**0.55**

Appendix G: Comparison of EPMA Data from Campaign 2

G.1. Comparison of the lime content of a range of samples taken by EPMA (under the same conditions as that described in Appendix E) compared against LA-ICP-MS analysis performed under the conditions of Campaign 2. Samples are taken from a separate study. The results demonstrate a small difference in the lime by 2.5 R% in the LA-ICP-MS samples which is less than that indicated by the analysed standards. Results as wt %

Sample	LA-ICP-MS	EPMA	Difference	R% Difference
1	10.04	9.77	0.26	2.61
2	10.33	10.00	0.34	3.25
3	10.15	9.92	0.23	2.24
4	10.29	10.26	0.03	0.30
5	10.01	9.92	0.09	0.94
6	9.34	9.15	0.19	2.08
7	10.21	9.84	0.38	3.68
8	5.80	5.53	0.27	4.68
9	7.32	6.96	0.36	4.91
10	9.83	9.53	0.30	3.07
11	9.97	9.88	0.09	0.93
12	7.58	7.46	0.12	1.53
13	7.65	7.52	0.13	1.64
14	9.22	8.75	0.47	5.05
15	10.43	10.46	-0.03	-0.31
16	8.80	8.33	0.47	5.33
17	6.56	6.23	0.33	5.07
18	9.31	9.19	0.12	1.30
19	10.51	10.42	0.09	0.83
20	10.31	10.26	0.05	0.48
21	10.54	10.44	0.11	1.01
22	9.66	9.15	0.50	5.19
23	7.87	7.71	0.17	2.10
24	9.36	9.04	0.31	3.36
25	11.61	11.21	0.40	3.42
26	11.53	11.25	0.28	2.43
27	7.76	7.44	0.32	4.08
28	11.64	11.37	0.27	2.33
29	9.27	9.22	0.04	0.48
30	9.60	9.27	0.33	3.45
31	7.44	7.19	0.25	3.30
32	9.34	9.32	0.01	0.13
33	10.04	9.95	0.09	0.85
34	9.68	9.68	0.00	-0.02
35	8.87	8.71	0.16	1.85
36	9.57	9.49	0.07	0.78
37	8.47	8.04	0.43	5.04
38	8.56	8.35	0.22	2.55
		Average	**0.22**	**2.42**
	Standard Deviation		*0.15*	*1.69*

Appendix H: Natron Glass Analytical Results

J.1. The analytical results for the natron glass. The samples are categorised by compositional group in order of sample name. Major and minor elements at wt%, trace elements as ppm. Detection limits see chapter 5. Fresh or recycled glass marked as identified in Chapter 6.

				Major and minor elements as wt %									
Apollonia-type	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
AH 3746 07	N-1	yellowish green	fresh	13.36	0.70	3.16	72.20	0.15	0.91	0.55	8.30	0.08	0.46
AY 2844 05	N-1	greenish-bluish	recycled	15.61	0.62	3.17	70.02	0.06	0.91	0.84	8.18	0.06	0.37
BSH 2885 06	N-1	very pale green	recycled	13.37	0.67	2.91	71.72	0.18	0.87	0.85	8.69	0.08	0.49
CEA W2S3 01	N-1	greenish?	recycled	17.63	0.68	3.20	66.30	0.15	0.99	1.00	9.41	0.07	0.42
CEA W2S3 02	N-1	pale blue	recycled	13.10	0.66	3.07	73.06	0.06	0.77	0.41	8.12	0.09	0.53
JER 3835 01	N-1	colourless with greenish tinge	recycled	12.29	0.57	3.34	71.89	0.16	0.92	0.85	9.26	0.08	0.49
JER 3835 02	N-1	pale blue	recycled	12.99	0.59	3.14	71.90	0.08	0.78	0.59	9.21	0.08	0.49
JER 3835 03	N-1	colourless	recycled	13.57	0.63	3.11	71.19	0.07	0.89	0.50	9.37	0.07	0.43
JER 3835 04	N-1	pale green	recycled	15.13	0.57	3.09	69.31	0.11	0.93	0.48	9.69	0.07	0.47
JER 3835 05	N-1	greenish blue	recycled	13.79	0.69	3.41	69.92	0.12	0.85	0.68	9.27	0.11	0.67
JER 5124 01	N-1	greenish-blue	recycled	14.81	0.46	3.26	72.55	0.05	0.81	0.52	6.80	0.09	0.50
JER 5124 02	N-1	greenish-blue	fresh	14.33	0.42	3.21	72.68	0.05	0.89	0.56	7.28	0.07	0.39
JER 5124 03	N-1	greenish-blue	fresh	15.35	0.43	3.04	72.16	0.05	0.93	0.52	6.93	0.07	0.39
JER 5124 04	N-1	light greenish-blue	fresh	14.01	0.53	3.53	71.72	0.06	0.73	0.49	8.06	0.11	0.63
JER 5124 05	N-1	greenish-blue	fresh	13.98	0.50	3.25	72.72	0.07	0.68	0.43	7.61	0.10	0.54
JER 5124 06	N-1	greenish-blue	fresh	14.25	0.52	3.14	72.24	0.06	0.83	0.55	7.77	0.08	0.44
JER 5124 08	N-1	greenish-blue	fresh	15.61	0.65	3.05	69.29	0.05	0.75	0.39	9.47	0.10	0.51
JER 5124 11	N-1	greenish-blue	recycled	14.40	0.68	3.13	68.84	0.18	0.78	0.89	10.31	0.10	0.54
JER 5124 12	N-1	pale greenish-blue	recycled	14.28	0.48	3.27	72.72	0.06	0.68	0.53	7.21	0.10	0.54
JER 5124 13	N-1	green	fresh	15.16	0.45	3.03	72.58	0.06	0.89	0.58	6.65	0.08	0.41
JER 5124 14	N-1	pale blue	fresh	14.98	0.59	3.18	70.02	0.05	0.73	0.47	9.18	0.10	0.56
JER 5124 15	N-1	pale blue	fresh	14.52	0.49	3.20	73.18	0.05	0.73	0.51	6.57	0.10	0.52
JER 5124 16	N-1	pale blue	recycled	14.64	0.49	3.14	72.35	0.06	0.82	0.54	7.22	0.08	0.46

Apollonia-type	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3
JER 5124 17	N-1	greenish-blue	recycled	15.62	0.51	3.34	69.94	0.06	0.87	0.56	8.38	0.09	0.49
JER 5124 20	N-1	greenish-blue	recycled	14.26	0.51	3.03	72.88	0.05	0.90	0.45	7.31	0.07	0.41
JER 5124 21	N-1	greenish-blue	fresh	15.36	0.46	2.97	71.95	0.05	0.88	0.57	7.13	0.08	0.41
JER 5124 23	N-1	greenish-blue	fresh	13.47	0.51	3.22	72.14	0.05	0.84	0.60	8.53	0.08	0.42
JER 5124 24	N-1	greenish-blue	recycled	15.04	0.49	3.05	71.80	0.05	0.86	0.53	7.45	0.09	0.48
JER 5124 25	N-1	greenish-blue	recycled	14.92	0.40	3.01	72.29	0.05	0.78	0.57	7.31	0.09	0.43
JER 5124 26	N-1	greenish-blue	recycled	15.16	0.61	2.82	72.05	0.04	0.88	0.43	7.42	0.07	0.40
JER 5124 27	N-1	green	recycled	14.47	0.65	2.79	70.98	0.17	0.72	0.95	8.48	0.10	0.54
JER 5124 29	N-1	olive green	fresh	13.89	0.46	3.26	72.86	0.07	0.96	0.77	7.06	0.09	0.45
RAM 3592 01	N-1	greenish	recycled	14.30	0.68	3.19	69.09	0.14	0.77	1.09	9.88	0.10	0.56
RAM 4740 07	N-1	very pale blue	recycled	13.98	0.59	3.28	70.61	0.12	0.74	0.71	9.21	0.09	0.51
RAM 6297 04	N-1	light greenish blue	recycled	12.64	0.54	3.27	71.46	0.12	0.75	0.52	9.96	0.08	0.48
RAM 5947 14	N-1	pale green	recycled	14.46	0.50	3.50	72.80	0.09	0.72	0.51	6.50	0.10	0.68
SEP 3791 01	N-1	very pale blue	recycled	14.67	0.50	3.02	71.14	0.11	0.82	0.60	8.57	0.06	0.38
SEP 3791 02	N-1	very pale blue	recycled	13.28	0.54	2.99	73.33	0.09	0.81	0.50	7.83	0.06	0.44
SEP 3791 03	N-1	very pale blue	recycled	12.97	0.55	2.85	72.88	0.13	0.83	0.56	8.60	0.06	0.39
SEP 3791 04	N-1	pale yellowish green	recycled	14.79	0.52	3.06	71.73	0.11	0.92	0.66	7.60	0.06	0.39
SEP 3791 05	N-1	colourless with pale green tinge	recycled	15.96	0.60	2.99	70.63	0.12	0.91	0.79	7.35	0.07	0.43
SEP 3791 06	N-1	olive green	recycled	14.77	0.59	3.16	70.04	0.19	0.93	0.67	8.92	0.07	0.50
SEP 3791 07	N-1	pale bluish green	recycled	15.33	0.54	3.26	67.89	0.18	0.62	0.66	10.79	0.07	0.49
SEP 3791 08	N-1	greenish blue	recycled	13.02	0.66	3.45	69.38	0.18	0.68	0.57	11.29	0.08	0.53
SEP 3791 09	N-1	green-olive green	recycled	13.81	0.59	3.27	71.06	0.17	0.83	0.56	9.05	0.08	0.45
SEP 3791 10	N-1	light blue	recycled	13.66	0.65	3.37	69.86	0.16	0.80	0.59	10.18	0.08	0.51
SEP 3791 11	N-1	light blue	recycled	14.61	0.65	3.02	71.94	0.10	0.90	0.55	7.63	0.07	0.41
SEP 3791 12	N-1	pale greenish-blue	fresh	14.11	0.56	3.30	72.65	0.06	0.84	0.48	7.32	0.08	0.48
TIB 5583 02	N-1	light greenish blue	recycled	13.42	0.76	3.47	69.30	0.12	0.67	0.50	10.86	0.10	0.57
TIB 5583 03	N-1	light greenish blue	recycled	13.64	0.61	3.42	70.77	0.12	0.85	0.74	9.21	0.07	0.44
TIB 5583 04	N-1	greenish blue	recycled	13.39	0.54	3.38	72.33	0.12	0.83	0.85	7.71	0.12	0.58
TIB 5583 05	N-1	brown	recycled	13.70	0.45	3.37	72.48	0.11	1.01	0.62	7.57	0.08	0.47
TR 6055 01	N-1	‘smokey’ pale blue	fresh	14.08	0.51	3.14	72.60	0.06	0.77	0.59	7.59	0.08	0.46
TR 6055 03	N-1	greenish blue	recycled	14.59	0.64	2.77	70.28	0.16	0.87	1.15	8.87	0.08	0.44

N-2 Bet Eli'ezer	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3
AH 3746 01	N-2	pale blue	fresh	11.77	0.37	2.82	75.91	0.10	0.75	0.47	7.33	0.05	0.30
AH 3746 04	N-2	pale blue	fresh	13.09	0.54	3.31	74.01	0.11	0.70	0.65	6.85	0.09	0.52
AH 3746 08	N-2	pale blue	fresh	12.04	0.47	3.43	74.39	0.11	0.70	0.60	7.70	0.06	0.37
AH 3746 12	N-2	pale blue	recycled	10.45	0.43	3.06	73.35	0.14	0.66	0.30	10.96	0.08	0.44
AH 3746 13	N-2	pale blue	recycled	12.36	0.42	2.90	75.71	0.09	0.71	0.49	6.76	0.06	0.38
HB 3032 01	N-2	brown glass	fresh	11.48	0.60	3.32	75.45	0.07	0.74	0.42	7.25	0.08	0.46
JER 5124 07	N-2	pale blue	fresh	13.80	0.46	3.05	73.84	0.06	0.80	0.60	6.70	0.09	0.48
JER 5124 18	N-2	green	recycled	11.33	0.56	3.27	73.92	0.10	0.54	0.63	8.02	0.11	0.71
JER 5124 19	N-2	greenish-blue	fresh	12.64	0.44	3.22	74.94	0.05	0.74	0.60	6.70	0.09	0.45
JER 5124 22	N-2	greenish-blue	fresh	12.51	0.44	3.12	75.35	0.06	0.76	0.78	6.36	0.08	0.41
JER 5124 30	N-2	greenish blue	recycled	12.99	0.46	3.29	75.22	0.06	0.67	0.49	5.99	0.11	0.60
NS 6362 01	N-2	light greenish blue	recycled	11.33	0.59	3.28	75.18	0.07	0.76	0.53	7.60	0.08	0.46
NS 6362 02	N-2	olive green	recycled	11.49	0.59	3.47	73.61	0.11	0.54	0.68	7.78	0.10	0.73
RAM 6490 01	N-2	greenish blue	fresh	13.61	0.53	3.48	73.66	0.06	0.65	0.53	6.72	0.09	0.55
RAM 5947 09	N-2	greenish blue	recycled	12.04	0.65	3.41	74.81	0.08	0.69	0.40	7.26	0.08	0.45
TR 6055 04A[†]	N-2	light blue	recycled	11.29	0.55	3.55	75.06	0.07	0.76	0.46	7.47	0.10	0.55
TR 6055 04B[†]	N-2	light blue	recycled	11.95	0.54	3.51	74.44	0.06	0.68	0.39	7.65	0.10	0.55
Egypt II	**Group**	**Colour**	**Recycled**	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3
AH 3746 02	N-3	greenish blue	fresh	13.06	0.52	2.49	72.07	0.11	1.11	0.32	8.94	0.27	0.99
AH 3746 05	N-3	pale blue	fresh	12.85	0.74	2.83	71.23	0.18	0.77	0.62	9.52	0.17	0.76
AH 3746 06	N-3	green	recycled	12.98	0.57	2.77	71.87	0.16	1.02	0.28	9.05	0.25	0.92
AH 3746 09	N-3	green	recycled	12.31	0.78	3.06	70.25	0.23	0.78	0.63	10.63	0.18	0.81
AH 3746 11	N-3	greenish blue	recycled	13.46	0.62	2.64	70.41	0.13	0.96	0.32	9.72	0.28	1.02
AY 2989 01	N-3	greenish	fresh	13.65	0.64	2.76	70.50	0.09	1.10	0.27	9.55	0.29	1.02
AY 2989 02	N-3	yellowish	recycled	15.60	0.60	2.82	68.41	0.11	0.84	0.44	9.73	0.20	0.89
AY 2989 03	N-3	greenish	fresh	13.85	0.72	2.80	70.39	0.10	0.96	0.34	9.42	0.27	1.01
AY 2989 05	N-3	greenish blue	fresh	15.10	0.51	2.62	68.92	0.08	1.11	0.25	10.08	0.28	0.93
CEA W2S3 03	N-3	greenish blue	fresh	13.40	0.57	2.57	70.71	0.08	1.04	0.26	9.91	0.29	1.02
HB 3032 02	N-3	greenish blue	fresh	13.80	0.54	2.40	70.72	0.08	1.08	0.36	9.65	0.29	0.95
HB 3032 03	N-3	dull greenish blue	fresh	14.67	0.49	2.42	70.49	0.07	1.07	0.25	9.20	0.28	0.93
HB 3032 05	N-3	greenish blue	fresh	14.29	0.54	2.39	70.42	0.07	1.08	0.25	9.60	0.29	0.94

Egypt II	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3
HB 3032 10	N-3	yellowish brown	fresh	14.44	0.76	2.47	70.13	0.08	1.25	0.24	9.27	0.27	0.95
JER 5124 10	N-3	pale green	recycled	18.36	0.52	1.88	70.56	0.08	1.09	0.30	6.17	0.22	0.69
JER 5124 28	N-3 (Mn)	pale green	-	14.67	0.57	2.25	69.34	0.09	1.22	0.30	9.29	0.29	0.94
NS 6362 03	N-3	greenish blue	fresh	14.72	0.50	2.21	71.42	0.07	1.06	0.25	8.71	0.18	0.77
NS 6362 05	N-3	light blue	fresh	14.58	0.44	2.21	70.83	0.06	1.05	0.24	9.42	0.24	0.82
NS 6362 07	N-3	greenish blue	fresh	13.52	0.59	2.66	70.76	0.09	1.03	0.39	9.48	0.30	1.05
NS 6362 08	N-3 (Mn)	colourless	-	14.58	0.58	2.41	68.39	0.11	0.95	0.36	9.69	0.28	1.09
NS 6362 09	N-3	greenish blue	fresh	14.28	0.52	2.35	70.07	0.09	0.99	0.33	10.05	0.28	0.92
RAM 4740 01	N-3	pale greenish blue	fresh	12.02	0.68	2.64	72.28	0.11	1.05	0.29	9.51	0.29	1.00
RAM 4740 03	N-3	blue	recycled	12.41	0.88	2.98	70.67	0.13	0.86	0.28	10.09	0.33	1.18
RAM 4740 09	N-3	pale blue	recycled	14.22	0.49	2.26	69.39	0.09	1.22	0.22	10.86	0.28	0.85
RAM 4768 01	N-3	very pale greenish blue	fresh	13.76	0.51	2.32	71.58	0.09	1.09	0.21	9.12	0.27	0.92
RAM 4768 02	N-3	greenish blue	fresh	13.51	0.51	2.41	71.61	0.09	1.09	0.20	9.24	0.27	0.93
RAM 4768 03	N-3	greenish blue	recycled	13.15	0.58	2.35	71.55	0.11	1.04	0.27	9.57	0.28	0.93
RAM 4768 07	N-3	green	fresh	13.20	0.49	2.51	72.14	0.07	1.23	0.18	8.96	0.24	0.87
RAM 5947 01	N-3	greenish blue	fresh	14.41	0.47	2.63	68.38	0.08	1.05	0.21	11.59	0.23	0.83
RAM 5947 02	N-3	greenish blue	fresh	12.88	0.53	2.55	72.06	0.09	1.05	0.18	9.31	0.27	0.95
RAM 5947 04	N-3	greenish blue	recycled	14.97	0.44	2.39	72.08	0.07	0.98	0.18	7.48	0.26	0.97
RAM 5947 05	N-3	pale blue	fresh	15.18	0.46	2.35	70.09	0.09	1.03	0.22	9.36	0.24	0.85
RAM 5947 06	N-3	yellowish green	recycled	15.02	0.63	2.93	68.66	0.12	0.82	0.37	9.98	0.23	0.89
RAM 5947 07	N-3	greenish blue	fresh	14.95	0.52	2.53	69.79	0.09	1.10	0.21	9.49	0.27	0.92
RAM 5947 08	N-3	pale blue	fresh	14.50	0.52	2.64	69.86	0.09	1.12	0.21	9.66	0.29	0.99
RAM 5947 10	N-3	greenish blue	fresh	14.98	0.55	2.62	69.88	0.10	1.08	0.38	9.17	0.25	0.88
RAM 5947 11	N-3	greenish blue	fresh	14.39	0.52	2.71	70.25	0.09	0.92	0.26	9.49	0.28	0.96
RAM 5947 12	N-3	greenish blue	fresh	13.55	0.41	2.43	69.64	0.08	0.89	0.20	11.79	0.19	0.71
RAM 5947 13	N-3	greenish blue	fresh	14.51	0.55	2.62	70.29	0.10	1.04	0.36	9.26	0.25	0.89
RAM 5947 15	N-3	greenish blue	fresh	13.96	0.50	2.60	71.25	0.08	1.05	0.19	9.00	0.27	0.98
RAM 5947 16	N-3	greenish blue	fresh	14.34	0.49	2.44	71.25	0.10	1.01	0.25	8.77	0.26	0.95
RAM 5947 18	N-3	greenish blue	fresh	12.94	0.56	2.77	71.02	0.09	1.14	0.18	9.91	0.30	0.97
RAM 5947 19	N-3	greenish blue	fresh	13.76	0.52	2.75	70.84	0.09	1.03	0.19	9.50	0.25	0.94
RAM 5947 20	N-3	pale blue	recycled	12.50	1.78	2.01	70.52	0.21	0.83	0.98	9.90	0.19	0.79

Egypt II	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3
RAM 5947 21	N-3	greenish blue	recycled	16.62	0.54	2.38	68.04	0.11	1.09	0.39	9.43	0.28	0.98
RAM 5947 23	N-3	greenish blue	fresh	14.30	0.52	2.64	70.64	0.08	1.11	0.20	9.15	0.27	0.96
RAM 5947 24	N-3	greenish blue	fresh	15.04	0.35	1.97	70.64	0.07	1.09	0.17	9.73	0.17	0.65
RAM 5947 25	N-3	greenish blue	recycled	14.83	0.51	2.69	69.88	0.10	1.02	0.23	9.28	0.28	1.04
RAM 6490 02	N-3	greenish blue	fresh	13.85	0.41	2.09	70.08	0.07	0.98	0.30	11.01	0.21	0.87
RAM 6490 03	N-3	greenish blue	fresh	13.11	0.72	2.66	70.82	0.09	0.98	0.36	9.77	0.30	1.03
RAM 6490 04	N-3	light bluish green	fresh	15.60	0.49	2.46	69.66	0.07	0.99	0.26	9.17	0.26	0.93
RAM 6490 10	N-3	green	fresh	15.82	0.58	2.68	68.99	0.07	1.14	0.27	8.98	0.28	1.04
RAM 3592 03	N-3 (Co)	blue	-	13.65	0.75	2.73	68.66	0.13	1.06	0.41	10.09	0.29	1.53
RAM 6297 06	N-3 (Co)	blue	-	14.04	0.73	2.71	68.89	0.10	0.99	0.40	9.75	0.28	1.45
TIB 5583 06	N-3 (Co)	blue	-	15.21	0.53	2.54	68.44	0.11	1.07	0.31	9.65	0.26	1.28
Egypt I	**Group**	**Colour**	**Recycled**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
AH 3746 10	N-4	greenish blue	fresh	16.07	0.81	4.38	72.13	0.11	0.89	0.42	2.67	0.55	1.81
TIB 5583 01	N-4	greenish blue	fresh	18.06	0.86	4.53	69.75	0.05	1.07	0.43	2.76	0.54	1.76
Outliers	**Group**	**Colour**	**Recycled**	**Na_2O**	**Mg O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**Fe_2O_3**
AH 3746 03	Outlier	greenish blue	-	13.40	0.58	2.67	70.76	0.16	0.95	0.50	8.49	0.13	1.13
NS 6362 04	Outlier	light greenish blue	-	15.30	0.72	3.28	68.46	0.13	0.70	0.55	9.45	0.14	0.88
NS 6362 10	Outlier	greenish blue	-	14.54	0.67	3.38	70.60	0.09	0.68	0.47	8.20	0.17	0.91
RAM 5947 03	Outlier	greenish blue	-	15.59	0.59	3.38	69.73	0.11	0.97	0.32	7.93	0.19	0.95
RAM 5947 22	Outlier	pale blue	-	15.80	0.66	2.80	68.01	0.15	0.85	0.52	9.40	0.18	0.89

	Trace elements as ppm																	
Apollonia-type	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AH 3746 07	3.2	241	17	22	169	bdl	5.8	5.5	11.4	3.2	2.2	8.1	511	9.1	53	1.82	0.53	bdl	bdl
AY 2844 05	5.6	360	12	16	220	1.5	4.1	21.8	9.5	4.4	0.5	13.0	538	8.6	47	1.57	0.89	0.03	bdl
BSH 2885 06	bdl	275	17	27	257	3.8	5.7	22.9	18.1	4.0	5.4	10.9	512	8.7	59	2.08	0.54	0.16	bdl
CEA W2S3 01	8.0	333	14	15	227	3.5	5.2	32.6	10.2	4.3	2.9	13.0	547	8.8	50	1.76	0.50	0.05	bdl
CEA W2S3 02	8.2	194	17	33	194	2.3	5.9	6.2	9.4	4.3	1.8	7.2	440	8.1	65	2.07	0.41	0.04	bdl
JER 3835 01	7.3	220	15	42	220	2.5	5.8	9.3	10.5	4.8	1.8	11.9	562	9.6	59	2.10	0.49	0.02	0.06
JER 3835 02	6.9	214	18	35	244	5.5	7.1	27.5	15.8	4.6	2.0	9.4	536	9.7	60	2.04	0.68	0.03	bdl
JER 3835 03	6.2	255	15	77	254	3.1	6.1	11.1	11.3	4.4	1.8	7.9	579	9.3	56	1.86	0.65	0.02	bdl
JER 3835 04	6.7	225	17	42	184	1.7	6.2	72.6	25.1	4.3	2.6	7.7	506	9.2	52	1.84	0.32	0.04	bdl
JER 3835 05	6.7	285	24	8	3381	3.8	10.1	19.5	16.4	5.0	2.3	11.0	529	9.9	64	2.48	0.75	0.06	bdl
JER 5124 01	11.0	143	17	44	190	1.9	5.0	12.8	8.9	4.6	2.0	10.3	447	9.2	67	2.35	0.27	0.04	bdl
JER 5124 02	8.9	157	14	n/a	173	1.5	3.9	4.1	12.3	4.3	1.9	10.7	474	8.7	55	1.96	0.35	0.02	bdl
JER 5124 03	9.2	157	14	n/a	168	1.5	3.9	4.6	7.3	3.9	1.8	9.9	441	8.7	57	1.97	0.46	0.03	bdl
JER 5124 04	13.1	157	22	n/a	229	2.4	6.1	5.1	10.2	4.9	2.2	9.8	526	10.7	76	2.93	0.48	0.01	bdl
JER 5124 05	12.0	144	18	n/a	218	2.1	5.5	6.2	8.3	4.4	1.7	8.6	437	9.2	66	2.51	0.52	0.02	bdl
JER 5124 06	12.7	161	15	n/a	186	1.7	4.6	7.1	8.1	4.3	2.3	10.5	500	9.3	60	2.13	0.40	0.02	bdl
JER 5124 08	11.5	219	17	n/a	202	2.0	5.2	4.1	8.2	4.3	1.7	7.2	534	9.9	73	2.47	0.14	0.02	bdl
JER 5124 11	9.7	239	19	n/a	229	3.6	6.8	18.0	13.9	4.4	2.7	12.0	561	9.8	70	2.46	0.79	0.03	bdl
JER 5124 12	13.4	132	19	n/a	202	2.1	5.4	5.9	10.8	4.4	1.7	10.3	432	9.6	72	2.59	0.40	0.02	bdl
JER 5124 13	9.8	151	15	n/a	174	1.6	4.2	4.5	7.5	4.1	1.6	10.8	426	8.4	61	2.06	0.29	0.02	bdl
JER 5124 14	11.8	174	19	n/a	232	2.2	5.8	5.3	8.2	4.5	2.1	9.1	579	9.6	65	2.54	0.40	0.00	bdl
JER 5124 15	11.7	149	18	n/a	204	2.0	6.1	5.0	8.9	4.5	1.9	9.9	418	9.1	67	2.45	0.30	0.20	bdl
JER 5124 16	10.9	149	16	110	199	1.8	4.6	32.5	10.0	4.2	2.0	10.3	482	9.4	62	2.25	0.31	0.11	bdl
JER 5124 17	10.7	145	17	111	215	1.8	4.9	5.6	8.3	4.5	2.1	10.7	567	10.3	65	2.42	0.29	0.03	bdl
JER 5124 20	9.5	118	13	134	177	1.6	4.1	5.2	7.4	4.1	3.3	9.2	480	9.0	58	2.01	0.14	0.03	bdl
JER 5124 21	11.3	150	15	103	179	1.6	4.2	4.8	9.5	4.1	1.5	10.8	453	8.8	61	2.07	0.29	0.03	bdl
JER 5124 23	10.9	141	14	n/a	199	1.6	6.3	4.9	19.0	4.2	1.8	11.2	581	9.2	59	2.12	0.29	0.06	bdl
JER 5124 24	12.1	173	18	23	196	1.9	4.8	8.1	7.4	4.3	2.0	10.1	494	8.9	62	2.28	0.46	0.08	bdl
JER 5124 25	12.0	106	15	24	176	1.7	4.4	4.0	7.5	4.2	1.8	11.0	453	9.0	68	2.23	0.18	0.02	bdl
JER 5124 26	10.6	122	14	n/a	173	1.5	4.0	3.6	6.6	3.9	1.6	8.3	464	8.7	57	2.00	0.25	0.03	bdl

Apollonia-type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	MnO	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
JER 5124 27	9.6	327	22	n/a	253	3.6	6.1	16.5	12.8	3.9	2.4	12.3	466	9.4	80	2.48	1.06	0.03	bdl
JER 5124 29	9.0	189	19	n/a	181	1.8	4.4	4.6	12.3	4.3	1.1	14.3	480	9.3	67	2.28	0.46	0.03	bdl
RAM 3592 01	9.2	294	21	24	470	4.8	6.9	33.5	17.2	4.3	2.9	13.6	523	9.5	73	2.32	0.78	0.04	bdl
RAM 4740 07	bdl	226	18	20	236	3.3	5.5	15.9	14.5	4.1	3.7	11.7	547	9.1	68	2.12	0.44	0.03	bdl
RAM 6297 04	7.6	295	16	21	414	4.1	6.6	69.4	16.8	4.6	1.7	8.6	539	9.3	57	1.93	0.40	0.09	bdl
RAM 5947 14	4.7	158	25	20	282	2.7	5.0	13.0	17.5	4.2	45.1	11.4	417	8.5	64	2.46	0.27	0.22	bdl
SEP 3791 01	bdl	164	15	19	145	0.9	4.4	23.5	14.5	3.8	2.6	9.4	469	7.9	45	1.48	0.24	0.02	bdl
SEP 3791 02	bdl	214	15	19	178	0.7	3.8	9.5	11.2	3.6	2.5	8.2	460	7.2	46	1.58	0.20	0.04	bdl
SEP 3791 03	bdl	323	14	18	309	1.6	4.1	21.7	15.4	3.3	4.0	9.1	508	8.3	49	1.55	0.57	0.29	bdl
SEP 3791 04	bdl	199	14	18	154	0.6	3.7	86.3	14.8	3.4	3.0	10.2	465	7.9	46	1.60	0.17	0.05	bdl
SEP 3791 05	bdl	310	17	20	158	0.7	4.4	72.1	15.4	3.5	3.4	11.3	458	7.9	58	1.77	0.35	0.02	bdl
SEP 3791 06	bdl	216	18	25	186	0.9	5.0	59.2	22.4	3.6	3.3	11.5	510	8.3	50	1.77	0.24	0.05	bdl
SEP 3791 07	bdl	243	21	26	192	0.7	5.1	48.6	24.8	3.4	2.8	8.6	516	9.7	53	1.86	0.37	0.07	bdl
SEP 3791 08	bdl	249	23	28	190	0.5	5.6	27.3	17.5	3.8	3.0	10.0	588	10.6	60	2.03	0.47	0.01	bdl
SEP 3791 09	bdl	253	18	23	161	0.8	5.1	6.6	8.8	3.2	2.8	8.9	516	9.1	54	1.85	0.41	0.01	bdl
SEP 3791 10	7.9	240	19	27	189	1.2	6.3	34.6	20.7	3.9	3.2	9.8	574	10.0	59	1.91	0.34	0.08	bdl
SEP 3791 11	bdl	275	16	25	149	0.5	3.6	12.8	8.9	3.1	2.3	9.3	479	8.3	57	1.75	0.23	0.00	bdl
SEP 3791 12	bdl	125	16	16	183	0.7	3.7	7.6	7.3	3.7	2.5	10.6	471	8.8	59	2.07	0.18	0.03	bdl
TIB 5583 02	10.7	240	21	27	512	3.3	8.5	336.3	47.6	4.9	3.0	9.0	536	9.9	69	2.27	0.61	0.30	bdl
TIB 5583 03	7.6	172	15	17	185	1.7	6.1	8.5	13.2	4.5	2.3	11.2	545	9.3	48	1.82	0.40	0.02	bdl
TIB 5583 04	8.5	165	21	30	263	2.3	7.6	71.7	21.3	4.6	1.9	14.0	424	8.6	69	2.26	0.30	0.05	bdl
TIB 5583 05	7.0	159	15	18	195	1.8	5.8	55.9	15.6	4.5	4.6	11.0	451	8.4	54	1.90	0.18	0.04	bdl
TR 6055 01	10.9	130	16	17	196	1.7	4.7	4.7	6.4	4.1	1.7	10.8	492	8.9	62	2.16	0.30	0.03	bdl
TR 6055 03	7.2	283	16	22	275	4.5	5.4	36.6	12.0	3.7	2.4	11.8	466	8.7	67	2.02	0.65	0.06	bdl
N-2 Bet Eli'ezer	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AH 3746 01	bdl	232	11	20	140	bdl	4.0	2.2	11.1	3.4	2.1	9.3	425	7.6	42	1.40	0.44	bdl	0.09
AH 3746 04	15.7	186	18	21	227	bdl	5.5	3.0	8.3	4.0	2.1	12.4	430	8.5	62	2.26	0.33	bdl	bdl
AH 3746 08	bdl	147	13	22	189	bdl	4.1	3.9	6.7	3.3	1.7	10.3	457	8.3	46	1.63	0.22	bdl	0.08
AH 3746 12	0.4	228	20	25	184	bdl	6.1	16.1	14.7	3.0	1.9	6.6	522	9.5	56	1.92	0.47	bdl	bdl
AH 3746 13	3.3	164	13	17	157	bdl	4.2	3.7	8.0	3.4	1.9	8.3	396	6.7	40	1.55	0.25	bdl	bdl
HB 3032 01	9.3	158	15	16	185	1.8	4.7	3.3	7.3	4.3	1.3	7.8	477	8.5	56	2.05	0.38	bdl	bdl
JER 5124 07	10.0	166	17	n/a	184	1.8	4.9	3.9	8.0	4.2	2.0	11.8	432	8.8	67	2.33	0.34	bdl	0.05

N-2 Bet Eli'ezer	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	MnO	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
JER 5124 18	11.4	147	21	135	235	2.5	7.3	44.9	18.1	4.4	2.5	9.1	413	9.4	79	2.71	0.37	0.68	0.07
JER 5124 19	9.1	113	15	93	180	1.7	4.7	3.8	8.3	4.4	1.7	11.3	446	8.8	64	2.34	0.26	0.05	bdl
JER 5124 22	10.4	136	14	162	171	1.7	4.6	3.9	7.4	3.8	1.4	12.2	454	8.1	60	2.08	0.30	bdl	bdl
JER 5124 30	9.8	106	20	n/a	194	2.2	5.8	9.6	10.2	4.5	1.4	10.2	399	9.3	79	2.84	0.30	bdl	bdl
NS 6362 01	9.4	181	16	25	175	1.8	5.1	3.9	9.0	4.5	1.8	10.2	460	8.3	54	2.00	0.64	bdl	bdl
NS 6362 02	12.1	140	19	27	240	2.4	7.1	41.1	16.1	4.6	3.0	9.8	437	8.9	64	2.43	0.42	0.84	bdl
RAM 6490 01	12.7	162	18	n/a	193	2.1	5.4	5.0	8.3	4.9	0.5	10.3	453	9.0	64	2.37	0.43	bdl	bdl
RAM 5947 09	0.1	206	16	17	187	1.6	3.2	2.5	8.9	3.9	2.1	8.6	528	8.7	54	1.98	0.46	0.04	bdl
TR 6055 04A[†]	12.7	126	18	19	215	2.1	5.2	4.1	8.3	4.5	1.5	8.6	486	9.4	66	2.57	0.23	bdl	bdl
TR 6055 04B[†]	10.3	115	18	18	207	2.1	5.6	3.6	8.6	4.5	1.5	7.6	493	9.5	63	2.55	0.23	bdl	bdl
Egypt II	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AH 3746 02	3.1	175	39	43	237	bdl	8.2	2.0	20.2	3.5	1.5	5.5	192	7.9	251	4.88	0.19	bdl	bdl
AH 3746 05	12.0	268	29	33	1615	5.3	9.2	123.9	35.1	3.5	2.6	8.3	365	8.8	148	3.19	0.52	0.09	bdl
AH 3746 06	8.4	225	36	39	265	bdl	8.2	5.3	27.4	3.6	1.5	6.1	207	8.4	219	4.44	0.17	0.09	bdl
AH 3746 09	3.3	277	31	36	1621	5.1	9.4	124.9	46.8	3.6	3.1	9.1	392	9.8	165	3.39	0.64	0.17	bdl
AH 3746 11	bdl	260	39	44	2910	8.0	9.1	57.1	109.1	3.9	2.9	5.8	215	8.8	254	4.72	0.28	0.48	bdl
AY 2989 01	10.3	272	40	n/a	208	3.9	9.0	3.6	18.9	4.2	1.1	4.9	230	9.1	261	5.08	0.17	0.06	0.05
AY 2989 02	10.8	237	32	n/a	636	8.5	9.9	158.9	47.4	4.1	3.2	6.0	308	8.8	173	3.88	0.39	0.41	bdl
AY 2989 03	9.4	343	40	n/a	206	3.8	8.9	3.7	19.0	4.2	1.0	5.7	236	8.5	227	4.94	0.27	0.06	bdl
AY 2989 05	4.8	229	37	n/a	191	3.5	8.3	3.4	17.2	3.9	0.8	4.5	211	8.5	257	4.89	0.11	0.05	0.06
CEA W2S3 03	8.8	318	38	42	212	3.8	8.4	3.5	17.6	4.2	0.9	4.3	202	8.5	279	4.81	0.13	0.13	bdl
HB 3032 02	8.4	232	39	39	196	3.6	7.8	3.6	21.9	3.9	1.0	5.0	201	8.4	287	4.95	0.11	0.13	bdl
HB 3032 03	7.3	416	37	39	189	3.5	7.6	3.2	17.3	3.7	0.8	3.8	199	8.3	257	4.76	0.08	0.08	bdl
HB 3032 05	8.5	232	38	39	194	3.5	7.6	3.0	17.0	3.7	0.9	4.1	203	8.5	287	4.88	0.09	0.15	bdl
HB 3032 10	9.3	335	36	39	198	3.7	7.7	2.4	16.8	3.9	0.8	4.2	237	8.4	243	4.83	0.09	0.06	bdl
JER 5124 10	9.2	416	24	n/a	192	2.8	5.7	37.7	22.5	3.1	0.9	4.2	159	7.2	129	4.06	0.08	0.07	0.06
JER 5124 28	9.9	290	42	26	9126	5.5	9.7	15.0	59.4	4.1	1.4	4.7	218	9.1	282	5.19	0.51	0.08	0.05
NS 6362 03	8.7	272	28	33	155	2.9	6.6	2.9	14.3	3.5	0.9	3.9	184	6.8	142	3.44	0.27	0.09	bdl
NS 6362 05	7.8	213	32	40	174	3.1	7.3	3.1	15.2	3.5	0.9	4.1	189	7.7	234	4.23	0.08	0.08	0.07
NS 6362 07	10.3	222	42	45	273	4.0	8.6	4.8	18.5	4.3	1.2	6.4	209	8.8	271	5.16	0.24	0.08	0.10
NS 6362 08	10.1	245	42	42	14426	10.7	11.9	33.7	102.2	4.7	3.3	5.1	215	8.9	252	4.74	0.54	0.18	0.12

Egypt II	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	MnO	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
NS 6362 09	8.3	166	40	41	192	3.4	7.6	4.1	17.7	3.8	1.0	5.2	199	8.2	287	4.84	0.14	0.09	0.09
RAM 4740 01	2.7	300	39	41	193	3.4	8.0	2.6	17.8	3.8	3.0	5.3	209	8.7	285	4.97	0.14	0.05	bdl
RAM 4740 03	bdl	390	43	44	279	4.4	9.0	7.8	24.4	4.0	2.7	4.8	261	9.9	317	5.68	0.25	0.07	bdl
RAM 4740 09	bdl	274	32	33	230	3.2	6.6	3.7	16.7	3.3	2.3	4.0	186	8.6	282	4.84	0.04	0.05	bdl
RAM 4768 01	3.5	240	36	40	184	3.3	6.5	2.0	17.5	3.7	2.0	3.9	189	7.5	248	4.48	0.09	bdl	0.16
RAM 4768 02	bdl	243	36	40	185	3.3	6.2	1.9	18.1	3.5	1.9	3.8	191	8.0	262	4.47	0.05	bdl	0.11
RAM 4768 03	bdl	283	40	41	196	3.4	6.5	2.1	16.0	3.3	1.8	4.8	207	8.4	289	4.75	0.40	0.28	0.22
RAM 4768 07	bdl	111	33	52	194	3.2	6.9	1.6	15.3	4.1	1.9	3.9	194	8.0	212	4.29	0.06	bdl	0.13
RAM 5947 01	9.4	142	32	34	160	2.8	6.2	2.3	15.3	3.4	3.2	4.7	211	7.8	207	4.17	bdl	0.05	0.08
RAM 5947 02	5.8	300	38	40	189	3.1	6.3	2.4	18.0	3.6	2.2	4.1	208	8.1	235	4.54	bdl	0.05	0.11
RAM 5947 04	3.4	323	34	39	612	3.7	7.5	5.7	25.2	3.6	6.3	4.2	173	8.0	209	4.47	bdl	0.15	0.19
RAM 5947 05	bdl	421	32	36	184	3.0	6.5	4.3	18.2	3.3	2.5	4.3	187	7.9	228	4.07	bdl	0.06	0.11
RAM 5947 06	bdl	267	33	37	798	6.8	7.5	179.0	45.3	3.4	4.1	5.5	302	9.7	211	4.17	0.32	0.47	bdl
RAM 5947 07	0.7	220	36	133	195	3.3	7.3	4.9	17.9	3.5	2.5	4.4	205	8.8	257	4.56	bdl	bdl	0.07
RAM 5947 08	bdl	204	40	41	194	3.4	7.1	3.5	17.1	3.4	2.7	4.4	197	8.9	266	4.85	bdl	bdl	0.11
RAM 5947 10	bdl	221	36	38	180	3.1	6.1	3.6	16.9	3.4	2.0	7.3	212	8.2	214	4.40	0.30	bdl	bdl
RAM 5947 11	bdl	233	39	40	188	3.2	6.5	2.5	15.8	3.4	1.4	5.1	216	8.9	255	4.66	bdl	bdl	bdl
RAM 5947 12	bdl	246	27	30	142	2.3	4.4	2.1	14.2	3.0	2.7	4.3	198	7.4	173	3.70	bdl	0.05	0.05
RAM 5947 13	1.9	211	37	38	182	3.1	6.6	4.2	19.6	3.3	3.0	7.1	215	8.0	213	4.44	0.22	0.05	bdl
RAM 5947 15	bdl	297	38	39	185	3.1	6.0	2.0	19.4	3.4	2.0	4.2	198	8.3	230	4.55	bdl	bdl	bdl
RAM 5947 16	13.4	338	37	43	183	3.6	8.5	3.4	20.7	3.6	3.2	4.8	192	7.9	225	4.37	0.19	0.06	0.05
RAM 5947 18	2.7	268	41	60	192	3.3	7.9	1.3	18.1	4.1	1.9	4.1	207	9.8	312	5.27	0.17	bdl	0.13
RAM 5947 19	1.6	222	35	208	186	3.2	8.1	1.6	18.0	3.7	3.9	4.2	211	8.8	233	4.60	0.11	0.32	0.10
RAM 5947 20	bdl	295	31	46	1107	12.2	11.8	67.3	46.7	2.7	3.0	6.7	398	7.7	206	3.64	0.91	0.31	0.26
RAM 5947 21	2.1	232	41	61	221	3.2	7.6	8.5	19.3	3.4	5.7	7.3	209	8.7	280	4.68	0.46	0.26	bdl
RAM 5947 23	2.7	301	38	49	189	3.2	8.4	1.6	17.2	3.6	2.0	4.2	203	8.6	238	4.57	0.06	0.17	bdl
RAM 5947 24	1.2	350	24	64	125	2.1	5.1	1.5	12.3	2.5	5.4	3.7	157	7.4	133	3.35	0.11	bdl	bdl
RAM 5947 25	2.1	227	41	53	315	3.7	9.2	4.8	20.1	3.9	7.4	5.1	212	8.7	238	4.62	0.14	bdl	0.19
RAM 6490 02	7.6	431	25	n/a	234	3.0	6.6	4.7	19.1	3.9	4.3	3.3	172	7.2	152	4.06	0.11	0.08	0.06
RAM 6490 03	10.9	315	39	n/a	255	4.4	8.6	5.2	22.3	4.4	0.1	5.9	225	9.2	296	5.25	0.33	0.13	0.06
RAM 6490 04	8.3	229	34	n/a	196	3.6	7.9	3.9	16.0	4.0	bdl	4.7	196	8.3	241	4.47	0.10	0.10	bdl

Egypt II	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	MnO	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
RAM 6490 10	7.6	257	38	153	216	4.1	9.1	3.9	18.4	4.5	0.9	4.6	209	8.6	236	4.88	0.12	0.08	0.06
RAM 3592 03	10.4	312	41	43	3191	436.9	13.4	1252.4	368.2	6.2	4.3	5.7	247	9.1	263	4.98	1.25	0.48	0.07
RAM 6297 06	9.5	278	39	41	3379	588.7	16.2	960.4	617.5	6.6	3.4	5.5	229	8.7	257	4.82	1.03	0.36	bdl
TIB 5583 06	8.4	360	35	36	2345	742.4	17.5	803.8	1088.8	7.1	3.6	4.4	207	8.3	220	4.28	1.92	0.24	0.06
Egypt I	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AH 3746 10	bdl	204	77	99	398	1.5	13.7	2.7	34.2	5.5	1.3	9.0	214	12.2	245	6.50	0.01	bdl	bdl
TIB 5583 01	8.1	278	76	104	412	7.0	13.3	4.1	34.2	6.8	1.3	9.4	224	12.1	265	6.47	0.06	0.07	bdl
Outliers	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**MnO**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AH 3746 03	bdl	385	32	56	3596	15.7	15.6	705.7	40.2	3.9	14.7	6.7	390	8.1	109	2.69	1.55	0.30	0.14
NS 6362 04	13.6	207	28	36	685	8.5	10.7	331.7	56.9	4.8	4.0	7.6	418	9.4	94	3.33	0.62	0.43	bdl
NS 6362 10	14.1	198	30	31	306	5.4	8.7	52.2	27.3	4.9	2.4	7.7	372	9.7	107	3.78	0.43	0.20	bdl
RAM 5947 03	9.9	211	32	36	613	7.2	9.4	81.7	44.2	4.8	2.9	6.3	347	9.7	132	4.01	0.25	0.18	bdl
RAM 5947 22	bdl	255	33	156	1735	17.7	13.3	589.4	91.0	3.9	12.7	7.6	375	8.8	152	3.40	0.82	1.06	0.14

Apollonia-type	In	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
AH 3746 07	bdl	14.2	2.75	bdl	268	8.0	14.2	1.8	7.60	1.66	0.38	1.45	0.23	1.46	0.30	0.75	0.11	0.72
AY 2844 05	bdl	1.2	0.57	bdl	248	6.9	13.7	1.8	7.13	1.45	0.43	1.41	0.21	1.22	0.25	0.70	0.09	0.70
BSH 2885 06	bdl	12.7	2.73	bdl	234	7.8	14.8	1.8	7.59	1.51	0.37	0.98	0.22	1.38	0.29	0.75	0.10	0.76
CEA W2S3 01	bdl	1.4	0.40	0.09	253	7.3	14.6	1.8	7.36	1.55	0.47	1.47	0.21	1.25	0.27	0.70	0.10	0.71
CEA W2S3 02	bdl	2.1	bdl	0.07	232	7.2	14.0	1.8	6.92	1.40	0.44	1.36	0.20	1.20	0.25	0.67	0.09	0.66
JER 3835 01	bdl	1.5	bdl	0.08	282	8.7	16.9	2.0	7.84	1.61	0.47	1.33	0.23	1.37	0.29	0.76	0.10	0.68
JER 3835 02	bdl	3.6	0.30	bdl	258	8.5	16.1	1.9	7.62	1.53	0.46	1.30	0.24	1.30	0.29	0.74	0.11	0.67
JER 3835 03	bdl	2.8	0.60	bdl	296	8.2	15.7	1.9	7.36	1.49	0.46	1.27	0.22	1.28	0.29	0.75	0.10	0.69
JER 3835 04	bdl	6.1	0.05	bdl	248	8.2	15.4	1.9	7.33	1.46	0.44	1.23	0.21	1.29	0.27	0.70	0.10	0.66
JER 3835 05	bdl	12.9	2.69	0.07	282	9.0	17.6	2.0	8.04	1.57	0.47	1.41	0.26	1.40	0.29	0.81	0.11	0.72
JER 5124 01	bdl	2.9	0.45	0.11	261	8.9	17.1	2.0	7.78	1.51	0.45	1.27	0.23	1.28	0.28	0.71	0.10	0.67
JER 5124 02	bdl	0.7	0.05	0.10	265	8.3	16.1	1.9	7.23	1.39	0.46	1.17	0.20	1.18	0.27	0.69	0.10	0.64
JER 5124 03	bdl	0.7	0.05	0.10	250	8.1	15.5	1.8	7.10	1.39	0.43	1.15	0.21	1.17	0.26	0.66	0.10	0.61
JER 5124 04	bdl	0.7	0.04	0.11	268	10.4	20.1	2.3	8.92	1.72	0.52	1.42	0.25	1.49	0.31	0.87	0.12	0.78
JER 5124 05	bdl	0.7	0.05	0.10	261	9.1	17.5	2.0	7.77	1.58	0.47	1.27	0.22	1.27	0.28	0.67	0.09	0.62

Apollonia-type	In	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
JER 5124 06	bdl	1.0	0.04	0.10	267	8.8	16.8	2.0	7.42	1.48	0.47	1.23	0.22	1.24	0.27	0.76	0.10	0.63
JER 5124 08	bdl	0.7	bdl	0.07	240	9.3	18.3	2.1	7.88	1.56	0.45	1.30	0.23	1.36	0.29	0.79	0.11	0.66
JER 5124 11	bdl	2.3	0.84	0.09	260	9.4	18.4	2.1	8.11	1.59	0.48	1.32	0.23	1.39	0.29	0.77	0.11	0.69
JER 5124 12	bdl	1.1	0.09	0.10	258	9.3	17.9	2.1	7.92	1.53	0.47	1.29	0.23	1.28	0.28	0.75	0.11	0.72
JER 5124 13	bdl	0.8	bdl	0.10	252	8.4	16.0	1.9	7.06	1.39	0.42	1.15	0.20	1.20	0.25	0.68	0.09	0.62
JER 5124 14	bdl	1.2	bdl	0.09	264	9.6	19.9	2.2	8.15	1.59	0.49	1.31	0.23	1.38	0.30	0.78	0.10	0.71
JER 5124 15	bdl	9.2	bdl	0.10	254	9.0	17.6	2.0	7.80	1.47	0.45	1.20	0.22	1.23	0.26	0.74	0.10	0.61
JER 5124 16	bdl	7.0	0.15	0.10	265	9.0	17.1	2.0	7.66	1.47	0.44	1.24	0.23	1.24	0.28	0.74	0.09	0.66
JER 5124 17	bdl	1.1	bdl	0.10	270	9.7	18.8	2.1	8.42	1.60	0.50	1.32	0.26	1.42	0.29	0.76	0.10	0.71
JER 5124 20	bdl	0.7	bdl	0.08	255	8.7	16.4	1.9	7.17	1.37	0.47	1.17	0.22	1.21	0.26	0.67	0.10	0.58
JER 5124 21	bdl	0.8	bdl	0.09	260	8.4	16.2	1.9	7.26	1.38	0.43	1.14	0.21	1.20	0.26	0.69	0.10	0.64
JER 5124 23	bdl	0.8	bdl	0.09	263	8.7	17.6	2.0	7.47	1.48	0.46	1.21	0.21	1.29	0.27	0.72	0.10	0.62
JER 5124 24	bdl	3.4	bdl	0.08	276	8.9	18.0	2.0	7.62	1.47	0.47	1.13	0.20	1.23	0.27	0.68	0.10	0.64
JER 5124 25	bdl	0.9	bdl	0.09	258	8.6	17.0	1.9	7.21	1.44	0.45	1.15	0.20	1.28	0.26	0.65	0.10	0.62
JER 5124 26	bdl	0.8	bdl	0.06	244	8.4	16.5	1.9	7.11	1.38	0.44	1.13	0.20	1.19	0.25	0.69	0.09	0.61
JER 5124 27	bdl	1.8	0.46	0.08	226	9.0	17.1	1.9	7.44	1.45	0.43	1.21	0.22	1.30	0.28	0.74	0.10	0.69
JER 5124 29	bdl	0.6	bdl	0.08	271	9.0	17.3	1.9	7.43	1.60	0.44	1.24	0.21	1.26	0.26	0.70	0.10	0.65
RAM 3592 01	bdl	3.3	2.80	0.11	265	8.5	16.4	2.0	7.96	1.61	0.47	1.43	0.23	1.37	0.30	0.76	0.11	0.73
RAM 4740 07	bdl	100.5	1.00	0.06	244	8.1	15.2	1.9	7.89	1.52	0.42	1.42	0.24	1.36	0.30	0.75	0.11	0.76
RAM 6297 04	bdl	18.5	3.43	bdl	278	7.8	15.2	1.9	7.43	1.53	0.46	1.45	0.22	1.30	0.27	0.77	0.10	0.72
RAM 5947 14	bdl	13.9	0.29	0.10	254	8.2	16.3	2.0	7.98	1.68	0.45	1.50	0.22	1.42	0.29	0.79	0.10	0.74
SEP 3791 01	bdl	15.1	2.04	0.07	241	7.2	13.3	1.7	6.85	1.33	0.37	1.12	0.19	1.11	0.27	0.71	0.09	0.64
SEP 3791 02	bdl	11.5	2.08	bdl	230	6.9	13.3	1.7	6.52	1.41	0.34	1.17	0.20	1.13	0.24	0.67	0.09	0.56
SEP 3791 03	bdl	17.9	2.70	bdl	230	7.4	14.2	1.8	7.07	1.47	0.37	1.22	0.20	1.34	0.27	0.72	0.10	0.72
SEP 3791 04	bdl	20.6	1.26	bdl	233	7.1	13.3	1.6	6.83	1.35	0.33	1.22	0.20	1.17	0.26	0.70	0.10	0.66
SEP 3791 05	bdl	19.0	1.30	bdl	220	7.1	13.3	1.7	6.80	1.31	0.29	1.09	0.21	1.29	0.26	0.65	0.09	0.63
SEP 3791 06	bdl	17.4	1.23	bdl	248	7.7	14.4	1.8	7.77	1.43	0.34	1.36	0.21	1.26	0.27	0.71	0.09	0.68
SEP 3791 07	bdl	25.9	2.00	bdl	234	8.2	14.6	1.8	7.83	1.53	0.29	1.23	0.23	1.35	0.31	0.88	0.11	0.75
SEP 3791 08	bdl	16.7	0.99	bdl	337	8.8	15.9	2.0	8.56	1.98	0.38	1.63	0.26	1.68	0.33	0.95	0.14	0.72
SEP 3791 09	bdl	14.4	0.96	bdl	234	8.1	14.5	1.8	7.55	1.51	0.30	1.29	0.23	1.44	0.27	0.84	0.11	0.74
SEP 3791 10	bdl	19.4	1.08	bdl	306	8.8	15.7	2.1	8.29	1.77	0.42	1.58	0.25	1.53	0.33	0.91	0.12	0.80
SEP 3791 11	bdl	15.5	0.49	bdl	231	7.5	14.0	1.8	7.14	1.43	0.35	1.25	0.21	1.34	0.27	0.79	0.10	0.68

Apollonia-type	In	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
SEP 3791 12	bdl	14.0	0.52	bdl	249	8.2	15.3	1.9	7.81	1.61	0.39	1.34	0.25	1.39	0.30	0.81	0.10	0.71
TIB 5583 02	bdl	29.0	15.94	0.17	271	8.4	16.1	2.0	7.93	1.56	0.48	1.41	0.23	1.36	0.29	0.79	0.12	0.80
TIB 5583 03	bdl	1.6	0.15	0.15	273	8.0	15.3	1.9	7.48	1.54	0.46	1.46	0.22	1.26	0.28	0.71	0.11	0.70
TIB 5583 04	bdl	5.1	0.22	0.17	263	8.0	15.4	1.9	7.32	1.48	0.47	1.32	0.22	1.21	0.26	0.71	0.10	0.68
TIB 5583 05	bdl	5.2	0.19	0.19	264	7.5	14.3	1.8	7.25	1.33	0.45	1.24	0.20	1.17	0.24	0.64	0.10	0.67
TR 6055 01	bdl	0.8	bdl	0.10	256	8.4	16.6	1.9	7.50	1.37	0.42	1.23	0.21	1.14	0.26	0.67	0.10	0.63
TR 6055 03	bdl	4.9	1.78	0.08	226	8.0	15.6	1.8	6.81	1.50	0.40	1.15	0.20	1.16	0.24	0.66	0.09	0.59
N-2 Bet Eli'ezer	**In**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
AH 3746 01	bdl	10.3	5.50	0.05	217	6.5	12.4	1.5	6.28	1.28	0.35	1.22	0.16	1.17	0.24	0.61	0.09	0.65
AH 3746 04	bdl	12.0	4.26	0.08	229	7.8	14.8	1.8	7.68	1.59	0.37	1.34	0.22	1.32	0.28	0.75	0.11	0.73
AH 3746 08	bdl	13.2	3.53	bdl	250	7.5	13.7	1.7	7.43	1.54	0.35	1.33	0.19	1.30	0.27	0.71	0.10	0.68
AH 3746 12	bdl	12.3	3.06	bdl	224	8.1	14.5	1.9	7.75	1.55	0.33	1.38	0.21	1.45	0.27	0.76	0.11	0.74
AH 3746 13	bdl	10.7	1.89	bdl	225	6.4	13.0	1.5	6.23	1.22	0.29	1.07	0.17	1.02	0.21	0.56	0.08	0.58
HB 3032 01	bdl	0.9	0.07	0.09	266	8.1	15.9	1.8	7.30	1.41	0.44	1.34	0.20	1.17	0.25	0.70	0.09	0.64
JER 5124 07	bdl	0.9	bdl	0.12	248	8.8	16.8	2.0	7.36	1.49	0.45	1.25	0.20	1.23	0.26	0.69	0.10	0.64
JER 5124 18	0.22	72.4	6.43	0.12	245	9.3	17.2	2.0	7.76	1.44	0.46	1.29	0.21	1.30	0.27	0.76	0.11	0.67
JER 5124 19	bdl	1.1	bdl	0.10	272	8.8	17.0	1.9	7.27	1.48	0.46	1.14	0.21	1.22	0.26	0.68	0.10	0.62
JER 5124 22	bdl	0.7	bdl	0.09	249	8.1	15.6	1.8	6.83	1.33	0.40	1.04	0.19	1.19	0.25	0.64	0.09	0.57
JER 5124 30	bdl	0.9	bdl	0.10	256	9.5	18.3	2.0	7.88	1.50	0.45	1.25	0.21	1.28	0.27	0.72	0.10	0.69
NS 6362 01	bdl	0.9	0.44	0.15	263	7.7	14.8	1.8	6.85	1.36	0.44	1.24	0.20	1.11	0.25	0.65	0.10	0.64
NS 6362 02	0.22	68.0	7.23	0.15	257	8.4	16.3	2.0	7.58	1.56	0.46	1.38	0.22	1.22	0.26	0.67	0.10	0.72
RAM 6490 01	bdl	0.9	bdl	0.07	265	8.5	16.4	2.0	7.85	1.53	0.47	1.38	0.23	1.29	0.27	0.73	0.10	0.73
RAM 5947 09	bdl	13.3	0.14	0.06	259	8.0	15.2	1.9	7.72	1.64	0.46	1.43	0.22	1.34	0.30	0.74	0.12	0.76
TR 6055 04A[†]	bdl	0.7	0.07	0.10	275	9.3	18.2	2.1	7.89	1.51	0.47	1.43	0.23	1.31	0.27	0.74	0.10	0.76
TR 6055 04B[†]	bdl	0.7	0.06	0.08	277	9.2	18.2	2.1	7.98	1.56	0.46	1.36	0.22	1.24	0.27	0.69	0.10	0.71
Egypt II	**In**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
AH 3746 02	bdl	10.0	5.80	bdl	166	8.1	15.9	1.9	7.35	1.52	0.32	1.29	0.20	1.25	0.25	0.70	0.10	0.85
AH 3746 05	bdl	38.3	77.00	bdl	214	8.0	15.1	1.9	7.59	1.50	0.31	1.41	0.21	1.35	0.27	0.77	0.12	0.76
AH 3746 06	bdl	16.2	3.58	bdl	172	8.2	15.9	1.9	7.62	1.50	0.29	1.43	0.20	1.44	0.28	0.79	0.13	0.89
AH 3746 09	bdl	45.2	70.71	bdl	227	8.7	16.2	2.1	8.20	1.64	0.30	1.47	0.24	1.43	0.31	0.78	0.13	0.91
AH 3746 11	bdl	21.2	8.63	bdl	190	8.5	16.1	2.0	7.92	1.66	0.28	1.38	0.22	1.41	0.29	0.82	0.12	0.97

Egypt II	In	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
AY 2989 01	bdl	0.5	0.01	0.06	194	9.0	17.5	2.1	8.31	1.68	0.43	1.48	0.24	1.41	0.29	0.85	0.12	0.89
AY 2989 02	0.26	81.1	6.52	0.05	204	8.5	16.7	2.0	7.99	1.56	0.42	1.41	0.23	1.34	0.29	0.80	0.12	0.79
AY 2989 03	bdl	0.5	bdl	bdl	201	8.7	17.4	2.1	8.02	1.67	0.42	1.43	0.22	1.32	0.28	0.80	0.13	0.83
AY 2989 05	bdl	0.5	bdl	bdl	186	8.5	16.8	2.0	7.80	1.53	0.39	1.36	0.22	1.30	0.27	0.76	0.12	0.88
CEA W2S3 03	bdl	0.7	bdl	bdl	174	8.1	16.3	2.0	7.60	1.55	0.40	1.47	0.21	1.25	0.27	0.76	0.12	0.87
HB 3032 02	bdl	0.7	0.05	bdl	174	8.8	17.5	2.0	7.51	1.49	0.36	1.28	0.21	1.23	0.26	0.73	0.11	0.83
HB 3032 03	bdl	0.6	0.08	bdl	170	8.6	16.9	2.0	7.46	1.52	0.37	1.30	0.19	1.14	0.26	0.70	0.11	0.79
HB 3032 05	bdl	0.6	0.06	bdl	173	8.9	17.3	2.0	7.53	1.50	0.38	1.24	0.20	1.18	0.27	0.72	0.12	0.78
HB 3032 10	bdl	0.6	0.05	bdl	179	8.8	17.4	2.0	7.51	1.49	0.37	1.25	0.20	1.19	0.26	0.74	0.11	0.79
JER 5124 10	bdl	2.3	0.76	bdl	131	7.6	15.2	1.7	6.31	1.29	0.32	0.98	0.17	1.08	0.23	0.61	0.09	0.64
JER 5124 28	bdl	0.7	bdl	bdl	243	9.5	18.4	2.1	7.83	1.54	0.36	1.19	0.21	1.26	0.28	0.78	0.11	0.79
NS 6362 03	bdl	0.6	0.19	0.07	158	7.1	13.9	1.6	6.19	1.23	0.33	1.03	0.17	0.98	0.21	0.60	0.09	0.63
NS 6362 05	bdl	0.7	0.17	0.07	157	7.8	15.2	1.8	6.79	1.37	0.35	1.18	0.18	1.08	0.23	0.67	0.10	0.73
NS 6362 07	bdl	0.8	0.10	0.10	185	8.8	17.7	2.1	8.07	1.47	0.41	1.40	0.22	1.28	0.27	0.76	0.12	0.90
NS 6362 08	bdl	3.3	2.08	0.07	298	8.5	17.0	2.0	7.59	1.51	0.39	1.29	0.22	1.26	0.28	0.73	0.12	0.84
NS 6362 09	bdl	0.8	0.09	0.07	172	8.6	16.9	2.0	7.39	1.42	0.38	1.26	0.19	1.16	0.24	0.70	0.10	0.77
RAM 4740 01	bdl	12.2	0.60	bdl	175	8.9	16.9	2.1	8.33	1.74	0.36	1.49	0.22	1.40	0.28	0.83	0.13	0.93
RAM 4740 03	bdl	12.3	0.52	bdl	196	10.1	19.4	2.4	9.44	1.88	0.38	1.63	0.25	1.66	0.31	0.98	0.16	1.07
RAM 4740 09	bdl	22.9	0.41	bdl	147	8.4	16.2	2.0	7.96	1.61	0.34	1.34	0.22	1.35	0.28	0.83	0.12	0.89
RAM 4768 01	bdl	9.9	2.52	bdl	161	7.8	15.7	2.0	7.49	1.49	0.32	1.14	0.20	1.22	0.25	0.73	0.11	0.85
RAM 4768 02	bdl	12.6	2.24	bdl	161	7.8	15.1	1.9	7.29	1.37	0.34	1.14	0.20	1.21	0.26	0.77	0.12	0.87
RAM 4768 03	bdl	11.7	3.05	bdl	159	8.5	16.0	2.0	8.00	1.59	0.33	1.24	0.19	1.34	0.28	0.81	0.12	0.92
RAM 4768 07	bdl	12.4	1.34	bdl	157	7.7	14.4	1.8	7.05	1.35	0.32	1.09	0.20	1.20	0.26	0.74	0.11	0.84
RAM 5947 01	bdl	11.5	0.62	bdl	184	8.0	15.1	1.9	7.78	1.50	0.34	1.48	0.21	1.21	0.26	0.73	0.11	0.85
RAM 5947 02	bdl	12.5	0.56	bdl	169	8.1	16.1	2.0	7.60	1.46	0.41	1.33	0.21	1.31	0.28	0.77	0.12	0.84
RAM 5947 04	bdl	15.0	0.74	0.05	145	8.0	15.6	1.9	7.52	1.55	0.37	1.30	0.22	1.35	0.27	0.77	0.12	0.91
RAM 5947 05	bdl	14.7	0.39	bdl	155	8.0	14.9	1.9	7.38	1.46	0.37	1.35	0.20	1.29	0.28	0.78	0.11	0.89
RAM 5947 06	bdl	106.4	8.39	0.05	205	9.1	16.8	2.1	8.53	1.73	0.44	1.51	0.26	1.57	0.33	0.94	0.12	0.93
RAM 5947 07	bdl	14.6	0.16	bdl	168	8.6	16.0	2.0	8.07	1.55	0.39	1.46	0.23	1.39	0.31	0.85	0.13	0.94
RAM 5947 08	bdl	18.4	0.16	bdl	168	8.9	16.5	2.1	8.32	1.58	0.37	1.44	0.24	1.48	0.31	0.89	0.12	1.04
RAM 5947 10	bdl	15.8	0.18	0.07	186	8.2	15.2	1.9	7.59	1.55	0.34	1.37	0.22	1.29	0.28	0.79	0.12	0.87

Egypt II	In	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
RAM 5947 11	bdl	12.2	0.04	bdl	183	8.8	16.8	2.1	8.37	1.67	0.40	1.53	0.25	1.47	0.32	0.81	0.13	0.91
RAM 5947 12	bdl	13.9	0.05	bdl	166	7.5	14.0	1.8	7.05	1.49	0.32	1.29	0.19	1.26	0.25	0.74	0.11	0.76
RAM 5947 13	bdl	20.1	0.22	0.06	188	8.1	15.5	2.0	7.35	1.54	0.35	1.30	0.21	1.27	0.28	0.77	0.12	0.90
RAM 5947 15	bdl	10.7	0.10	bdl	177	8.5	16.9	2.1	8.19	1.63	0.38	1.29	0.22	1.37	0.28	0.83	0.11	0.95
RAM 5947 16	bdl	11.2	1.03	0.06	163	8.2	16.0	2.0	7.61	1.54	0.41	1.27	0.22	1.31	0.28	0.80	0.12	0.92
RAM 5947 18	bdl	13.9	1.05	bdl	181	9.5	17.9	2.2	8.70	1.78	0.47	1.44	0.25	1.61	0.33	0.97	0.13	1.06
RAM 5947 19	bdl	13.7	0.45	bdl	180	8.8	16.3	2.1	8.05	1.73	0.41	1.35	0.22	1.53	0.29	0.89	0.13	0.94
RAM 5947 20	bdl	32.2	4.49	bdl	162	8.2	15.7	1.8	6.92	1.54	0.38	1.03	0.21	1.21	0.29	0.79	0.11	0.81
RAM 5947 21	bdl	14.1	0.60	0.09	174	8.4	16.2	2.0	7.96	1.59	0.44	1.26	0.23	1.36	0.28	0.84	0.12	0.98
RAM 5947 23	bdl	11.3	0.35	bdl	175	8.6	16.7	2.1	7.75	1.66	0.41	1.26	0.23	1.35	0.29	0.85	0.11	0.89
RAM 5947 24	bdl	15.6	0.31	bdl	138	7.2	13.6	1.7	6.63	1.37	0.31	1.04	0.21	1.19	0.25	0.79	0.11	0.76
RAM 5947 25	bdl	14.6	0.25	bdl	178	8.8	16.8	2.1	8.12	1.72	0.42	1.40	0.24	1.41	0.30	0.85	0.11	0.95
RAM 6490 02	bdl	0.8	bdl	bdl	152	7.5	15.6	1.8	6.74	1.34	0.35	1.10	0.19	1.09	0.22	0.66	0.10	0.67
RAM 6490 03	bdl	1.4	bdl	bdl	189	9.3	18.0	2.2	8.29	1.66	0.42	1.45	0.24	1.33	0.31	0.84	0.13	0.91
RAM 6490 04	bdl	0.6	bdl	bdl	169	8.4	16.2	1.9	7.74	1.53	0.39	1.23	0.22	1.31	0.26	0.75	0.11	0.80
RAM 6490 10	bdl	0.8	bdl	0.05	184	8.8	17.3	2.1	7.96	1.58	0.41	1.29	0.23	1.29	0.28	0.81	0.12	0.82
RAM 3592 03	0.30	7.2	2.86	0.08	226	9.1	17.5	2.1	8.15	1.67	0.42	1.44	0.23	1.40	0.30	0.80	0.13	0.88
RAM 6297 06	0.97	6.9	0.62	bdl	210	8.4	16.6	2.1	8.05	1.63	0.38	1.46	0.23	1.31	0.28	0.76	0.11	0.91
TIB 5583 06	0.75	10.5	1.66	0.10	180	8.2	15.9	1.9	7.37	1.55	0.40	1.24	0.19	1.26	0.27	0.74	0.11	0.79
Egypt I	**In**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
AH 3746 10	bdl	13.7	2.49	bdl	216	11.2	23.1	2.7	11.88	2.39	0.53	2.07	0.34	2.13	0.42	1.14	0.17	1.25
TIB 5583 01	bdl	0.7	0.13	0.18	242	11.1	23.2	2.7	11.00	2.31	0.66	2.05	0.34	1.95	0.41	1.11	0.17	1.23
Outliers	**In**	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
AH 3746 03	bdl	110.4	2116.57	bdl	220	7.5	14.1	1.8	7.15	1.51	0.33	1.33	0.19	1.25	0.27	0.75	0.11	0.73
NS 6362 04	0.45	140.0	13.47	0.12	230	9.1	18.0	2.1	8.19	1.55	0.46	1.38	0.24	1.31	0.29	0.73	0.11	0.77
NS 6362 10	0.07	20.4	5.15	0.11	221	9.7	19.3	2.2	8.57	1.66	0.46	1.48	0.24	1.38	0.30	0.77	0.11	0.79
RAM 5947 03	bdl	42.5	3.87	0.08	214	9.7	18.8	2.3	9.00	1.78	0.47	1.58	0.26	1.52	0.32	0.90	0.13	0.95
RAM 5947 22	bdl	317.8	24.74	0.06	233	8.5	16.3	2.1	8.07	1.67	0.44	1.30	0.24	1.38	0.29	0.82	0.12	0.78

Apollonia-type	Lu_2O_3	HfO_2	Ta_2O_3	WO	Pt	Au	PbO	Bi	ThO_2	UO_2
AH 3746 07	0.11	1.25	0.11	0.08	bdl	bdl	5.0	bdl	1.04	0.74
AY 2844 05	0.09	1.01	0.09	0.06	bdl	bdl	7.4	bdl	0.85	0.62
BSH 2885 06	0.10	1.30	0.11	0.08	bdl	bdl	45.5	bdl	1.01	0.64
CEA W2S3 01	0.10	1.10	0.10	bdl	bdl	bdl	28.9	bdl	0.92	0.63
CEA W2S3 02	0.09	1.43	0.11	0.07	bdl	bdl	12.0	bdl	0.97	0.90
JER 3835 01	0.11	1.24	0.10	0.08	bdl	bdl	12.2	bdl	1.02	0.73
JER 3835 02	0.10	1.24	0.11	0.08	bdl	bdl	40.4	bdl	1.01	1.08
JER 3835 03	0.11	1.19	0.10	0.06	bdl	bdl	17.8	bdl	0.97	0.72
JER 3835 04	0.10	1.15	0.09	0.05	bdl	bdl	30.0	bdl	0.96	0.86
JER 3835 05	0.11	1.34	0.12	0.09	bdl	bdl	52.4	bdl	1.13	1.07
JER 5124 01	0.10	1.39	0.12	0.07	bdl	bdl	188.3	bdl	1.16	1.74
JER 5124 02	0.09	1.15	0.10	0.07	bdl	bdl	5.3	bdl	0.96	0.83
JER 5124 03	0.09	1.15	0.10	0.06	bdl	bdl	6.5	bdl	0.95	0.81
JER 5124 04	0.12	1.52	0.14	0.09	bdl	bdl	7.1	bdl	1.32	2.33
JER 5124 05	0.10	1.30	0.13	0.08	bdl	bdl	4.8	bdl	1.10	1.14
JER 5124 06	0.10	1.24	0.11	0.07	bdl	bdl	6.5	bdl	1.06	1.10
JER 5124 08	0.11	1.48	0.12	0.06	bdl	bdl	4.0	bdl	1.16	1.22
JER 5124 11	0.11	1.47	0.13	0.10	bdl	bdl	20.9	bdl	1.18	0.91
JER 5124 12	0.11	1.51	0.13	0.07	bdl	bdl	45.6	bdl	1.21	1.89
JER 5124 13	0.09	1.23	0.11	0.07	bdl	bdl	4.3	bdl	0.99	0.79
JER 5124 14	0.10	1.37	0.12	0.06	bdl	bdl	7.5	bdl	1.18	1.86
JER 5124 15	0.10	1.43	0.13	0.08	bdl	bdl	6.7	bdl	1.14	1.42
JER 5124 16	0.10	1.31	0.11	0.06	bdl	bdl	441.7	0.05	1.08	1.75
JER 5124 17	0.11	1.38	0.12	0.06	bdl	bdl	32.1	bdl	1.12	1.40
JER 5124 20	0.10	1.18	0.10	0.05	bdl	bdl	23.6	bdl	0.99	0.93
JER 5124 21	0.09	1.22	0.10	0.07	bdl	bdl	4.8	bdl	1.01	0.73
JER 5124 23	0.09	1.21	0.10	0.08	bdl	bdl	6.4	bdl	0.98	0.71
JER 5124 24	0.09	1.22	0.11	0.07	bdl	bdl	282.6	bdl	1.02	1.38
JER 5124 25	0.10	1.34	0.10	0.07	bdl	bdl	267.6	bdl	1.06	0.91
JER 5124 26	0.09	1.17	0.11	0.05	bdl	bdl	12.0	bdl	0.98	1.16
JER 5124 27	0.10	1.60	0.12	0.10	bdl	bdl	23.1	bdl	1.14	1.32
JER 5124 29	0.10	1.33	0.11	0.08	bdl	bdl	3.2	bdl	1.06	0.67
RAM 3592 01	0.11	1.49	0.12	0.09	bdl	bdl	56.3	bdl	1.10	1.09
RAM 4740 07	0.10	1.56	0.12	0.04	bdl	bdl	34.7	bdl	1.13	0.94
RAM 6297 04	0.10	1.26	0.11	0.07	bdl	bdl	141.5	bdl	1.00	0.97
RAM 5947 14	0.12	1.56	0.12	0.07	bdl	1.10	77.7	bdl	1.31	2.16
SEP 3791 01	0.10	1.06	0.10	bdl	bdl	bdl	23.7	bdl	0.91	0.84
SEP 3791 02	0.09	1.04	0.08	0.05	bdl	bdl	24.5	bdl	0.87	0.98
SEP 3791 03	0.10	1.15	0.10	0.07	bdl	0.05	253.4	bdl	0.93	0.68
SEP 3791 04	0.10	1.09	0.09	0.19	bdl	bdl	33.6	bdl	0.90	0.78
SEP 3791 05	0.09	1.37	0.11	0.07	bdl	bdl	23.8	bdl	0.97	0.88
SEP 3791 06	0.11	1.13	0.10	0.08	bdl	bdl	36.6	bdl	0.96	0.92
SEP 3791 07	0.11	1.34	0.11	0.06	bdl	bdl	142.5	bdl	1.10	2.74
SEP 3791 08	0.13	1.36	0.13	0.07	bdl	bdl	12.9	bdl	1.13	1.07
SEP 3791 09	0.10	1.30	0.11	0.07	bdl	bdl	15.6	bdl	1.07	0.87
SEP 3791 10	0.12	1.39	0.12	0.08	bdl	bdl	18.9	bdl	1.10	1.06
SEP 3791 11	0.10	1.38	0.11	bdl	bdl	bdl	10.1	bdl	1.01	1.12
SEP 3791 12	0.10	1.37	0.12	0.09	bdl	bdl	8.6	bdl	1.08	0.76
TIB 5583 02	0.10	1.52	0.11	0.08	bdl	bdl	191.1	0.06	1.05	1.22
TIB 5583 03	0.10	1.05	0.10	bdl	bdl	bdl	15.6	bdl	0.89	0.85
TIB 5583 04	0.10	1.48	0.12	0.07	bdl	bdl	63.3	bdl	1.02	0.85
TIB 5583 05	0.09	1.12	0.10	0.06	bdl	bdl	33.4	bdl	0.97	0.85
TR 6055 01	0.09	1.25	0.11	0.07	bdl	bdl	7.0	bdl	1.06	1.36

TR 6055 03	0.09	1.32	0.09	0.06	bdl	bdl	50.4	bdl	1.01	0.59
N-2 Bet Eli'ezer	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AH 3746 01	0.08	0.94	0.08	0.06	bdl	bdl	5.1	bdl	0.80	0.84
AH 3746 04	0.11	1.40	0.12	0.09	bdl	bdl	5.2	bdl	1.12	0.69
AH 3746 08	0.10	1.10	0.09	0.07	bdl	bdl	6.4	bdl	0.93	0.70
AH 3746 12	0.10	1.30	0.10	0.07	bdl	bdl	8.2	bdl	1.02	1.19
AH 3746 13	0.08	0.94	0.08	0.06	bdl	bdl	170.7	bdl	0.77	0.75
HB 3032 01	0.09	1.18	0.11	0.07	bdl	bdl	7.2	bdl	1.01	0.73
JER 5124 07	0.10	1.38	0.11	0.08	bdl	bdl	5.7	bdl	1.04	0.67
JER 5124 18	0.10	1.60	0.14	0.08	bdl	bdl	6496.6	0.60	1.24	0.78
JER 5124 19	0.10	1.35	0.11	0.08	bdl	bdl	5.1	bdl	1.04	0.65
JER 5124 22	0.08	1.21	0.11	0.06	bdl	bdl	6.3	bdl	0.98	0.64
JER 5124 30	0.10	1.60	0.14	0.10	bdl	bdl	6.2	bdl	1.26	0.74
NS 6362 01	0.09	1.16	0.11	0.07	bdl	bdl	12.6	bdl	0.94	0.81
NS 6362 02	0.10	1.30	0.13	0.08	bdl	bdl	7769.0	0.69	1.11	0.74
RAM 6490 01	0.10	1.39	0.13	0.07	bdl	bdl	12.0	bdl	1.13	0.78
RAM 5947 09	0.10	1.33	0.11	0.11	bdl	bdl	7.0	bdl	1.05	0.68
TR 6055 04A[†]	0.10	1.35	0.12	0.08	bdl	bdl	12.0	bdl	1.18	0.70
TR 6055 04B[†]	0.10	1.22	0.12	0.06	bdl	bdl	13.8	bdl	1.12	0.71
Egypt II	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AH 3746 02	0.13	5.28	0.26	0.09	bdl	bdl	1.9	bdl	1.76	0.89
AH 3746 05	0.11	3.26	0.18	0.12	bdl	bdl	306.8	bdl	1.46	0.97
AH 3746 06	0.14	4.80	0.27	0.08	bdl	bdl	7.3	bdl	1.85	1.08
AH 3746 09	0.14	3.50	0.19	0.14	bdl	bdl	294.9	bdl	1.63	1.09
AH 3746 11	0.14	5.31	0.27	0.37	bdl	bdl	159.5	bdl	1.96	1.14
AY 2989 01	0.15	5.43	0.28	0.08	bdl	bdl	2.5	bdl	1.87	0.91
AY 2989 02	0.12	3.62	0.21	0.15	bdl	bdl	1553.7	0.19	1.60	1.32
AY 2989 03	0.13	4.59	0.26	0.09	bdl	bdl	2.9	bdl	1.72	1.07
AY 2989 05	0.13	5.19	0.27	0.08	bdl	bdl	3.0	bdl	1.80	1.08
CEA W2S3 03	0.13	5.57	0.26	0.08	bdl	bdl	4.0	bdl	1.85	1.11
HB 3032 02	0.13	5.35	0.24	0.06	bdl	bdl	2.6	bdl	1.85	1.03
HB 3032 03	0.11	4.78	0.23	0.06	bdl	bdl	2.4	bdl	1.78	1.21
HB 3032 05	0.13	5.31	0.23	0.07	bdl	bdl	2.1	bdl	1.84	1.03
HB 3032 10	0.12	4.56	0.23	bdl	bdl	bdl	1.8	bdl	1.78	1.06
JER 5124 10	0.10	2.51	0.20	bdl	bdl	bdl	16.8	bdl	1.41	1.27
JER 5124 28	0.13	5.30	0.26	0.14	bdl	bdl	14.0	bdl	1.92	1.28
NS 6362 03	0.10	2.78	0.18	0.06	bdl	bdl	2.5	bdl	1.39	1.14
NS 6362 05	0.11	4.44	0.21	0.06	bdl	bdl	2.1	bdl	1.67	1.33
NS 6362 07	0.13	5.09	0.26	0.11	bdl	bdl	3.1	bdl	1.84	1.01
NS 6362 08	0.13	4.83	0.23	0.14	bdl	bdl	56.7	bdl	1.73	1.38
NS 6362 09	0.12	5.45	0.25	0.08	bdl	bdl	3.3	bdl	1.82	1.01
RAM 4740 01	0.14	6.27	0.27	0.06	bdl	bdl	4.8	bdl	2.05	0.96
RAM 4740 03	0.17	6.96	0.31	0.09	bdl	bdl	64.2	bdl	2.36	1.25
RAM 4740 09	0.14	6.15	0.27	0.05	bdl	bdl	19.4	bdl	1.96	0.98
RAM 4768 01	0.12	5.14	0.24	0.07	bdl	bdl	2.9	bdl	1.72	0.98
RAM 4768 02	0.14	5.55	0.23	0.08	bdl	bdl	3.2	bdl	1.79	1.05
RAM 4768 03	0.14	6.20	0.26	0.14	bdl	bdl	397.8	2.82	1.98	1.04
RAM 4768 07	0.12	4.49	0.23	0.08	bdl	bdl	4.0	bdl	1.56	0.77
RAM 5947 01	0.13	4.65	0.24	0.07	bdl	bdl	3.7	bdl	1.70	1.27
RAM 5947 02	0.12	5.24	0.25	0.07	bdl	bdl	6.7	bdl	1.82	1.06
RAM 5947 04	0.12	4.71	0.25	0.08	bdl	bdl	38.4	0.76	1.71	1.28
RAM 5947 05	0.13	5.05	0.23	0.06	bdl	bdl	6.5	bdl	1.84	1.15
RAM 5947 06	0.16	4.88	0.25	0.16	bdl	bdl	1221.6	0.16	1.97	1.36

RAM 5947 07	0.13	5.62	0.26	0.06	bdl	bdl	5.9	bdl	1.96	1.26
RAM 5947 08	0.14	5.90	0.28	0.06	bdl	bdl	6.2	bdl	2.08	1.20
RAM 5947 10	0.14	4.82	0.26	0.14	bdl	bdl	6.3	bdl	1.73	0.87
RAM 5947 11	0.15	5.63	0.28	0.06	bdl	bdl	2.4	bdl	2.03	1.51
RAM 5947 12	0.12	3.85	0.21	0.05	bdl	bdl	3.1	bdl	1.56	1.22
RAM 5947 13	0.12	4.83	0.25	0.13	bdl	bdl	4.9	bdl	1.72	0.84
RAM 5947 15	0.13	5.14	0.26	0.06	bdl	1.25	3.7	bdl	1.92	1.53
RAM 5947 16	0.13	5.17	0.25	0.08	bdl	bdl	7.1	bdl	1.91	1.37
RAM 5947 18	0.16	7.12	0.31	0.11	bdl	bdl	4.5	bdl	2.33	1.21
RAM 5947 19	0.15	5.25	0.27	0.06	bdl	bdl	6.1	bdl	2.06	1.34
RAM 5947 20	0.11	4.86	0.22	0.12	bdl	bdl	337.5	bdl	1.74	0.96
RAM 5947 21	0.14	6.38	0.26	0.14	bdl	bdl	8.7	bdl	2.02	1.01
RAM 5947 23	0.14	5.31	0.26	0.07	bdl	bdl	7.7	bdl	1.96	1.52
RAM 5947 24	0.12	3.08	0.20	0.05	bdl	bdl	5.6	bdl	1.46	1.20
RAM 5947 25	0.14	5.45	0.27	0.15	bdl	bdl	24.5	bdl	2.01	1.59
RAM 6490 02	0.10	3.02	0.20	0.05	bdl	bdl	4.3	bdl	1.39	1.13
RAM 6490 03	0.14	5.89	0.28	0.10	bdl	bdl	4.1	bdl	2.01	1.04
RAM 6490 04	0.13	4.82	0.25	0.05	bdl	bdl	2.9	bdl	1.77	1.39
RAM 6490 10	0.13	4.60	0.25	0.06	bdl	bdl	2.9	bdl	1.79	1.13
RAM 3592 03	0.14	5.28	0.25	0.09	bdl	bdl	531.7	bdl	1.85	1.13
RAM 6297 06	0.13	4.98	0.25	0.08	bdl	bdl	92.5	bdl	1.79	1.11
TIB 5583 06	0.12	4.49	0.21	0.07	bdl	bdl	82.3	bdl	1.63	1.35
Egypt I	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AH 3746 10	0.18	5.42	0.36	0.09	bdl	bdl	6.9	0.51	2.51	1.49
TIB 5583 01	0.18	5.40	0.32	0.09	bdl	bdl	3.9	bdl	2.28	1.55
Outliers	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AH 3746 03	0.13	2.37	0.15	0.19	bdl	bdl	4484.3	0.19	1.24	1.04
NS 6362 04	0.13	1.89	0.16	0.17	bdl	0.17	1635.5	0.26	1.37	1.14
NS 6362 10	0.12	2.14	0.18	0.11	bdl	bdl	1349.5	0.41	1.54	1.08
RAM 5947 03	0.13	3.02	0.23	0.10	bdl	bdl	527.4	0.09	1.78	1.24
RAM 5947 22	0.13	3.75	0.19	0.27	bdl	0.39	3310.6	0.48	1.57	1.24

[†] analysis A of vessel body, analysis B of trailed decoration

n/a = element not analysed for.

Appendix I: Cobalt and Manganese Coloured Plant Ash Glass Averages

I.1. Major and minor and selected trace oxides for N-3 Co and N-3 Mn, the cobalt and manganese de/coloured groups. Values as wt % unless otherwise specified. Group N-3F is the Egypt II "fresh" glass) reproduced from Table 6.8 provided as a comparison. Note raised levels iron oxide in N-3 Co.

Group	Glass Type	No.	Colour		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	Fe_2O_3	MnO‡	SrO‡	ZrO_2‡	Total Col*
N-3F	Egypt II "fresh" glass	37	greenish blue	**M**	**14.08**	**0.53**	**2.52**	**70.60**	**0.09**	**1.06**	**0.26**	**9.55**	**0.26**	**0.93**	**195**	**203**	**239**	**206**
				S.D	*0.83*	*0.08*	*0.19*	*0.92*	*0.02*	*0.07*	*0.06*	*0.67*	*0.03*	*0.09*	*29*	*16*	*41*	
N-3 Co	Egypt II Co added	3	blue	**M**	**14.30**	**0.67**	**2.66**	**68.66**	**0.11**	**1.04**	**0.37**	**9.83**	**0.27**	**1.42**	**2971**	**227**	**247**	**4802**
				S.D	*0.82*	*0.12*	*0.10*	*0.23*	*0.02*	*0.04*	*0.06*	*0.23*	*0.02*	*0.13*	*551*	*20*	*23*	
N-3 Mn	Egypt II Mn added	2	colourless/ pale green	**M**	**14.63**	**0.57**	**2.33**	**68.87**	**0.10**	**1.08**	**0.33**	**9.49**	**0.29**	**1.01**	**11776**	**216**	**267**	**11843**
				S.D	*0.06*	*0.00*	*0.11*	*0.68*	*0.02*	*0.19*	*0.04*	*0.28*	*0.01*	*0.10*	*3748*	*2*	*21*	

‡ MnO, SrO and ZrO2 as ppm; * Total Colourants = MnO+CoO+CuO+PbO (ppm)

I.2. Mean trace oxides (oxides as Table 2) for the cobalt and manganese de/coloured groups. Values as ppm. Group N-3F added for comparison.

Group		B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	Nb_2O_3	MoO	Ag	SnO_2	Sb_2O_3	BaO	HfO_2	Ta_2O_3	WO	PbO	ThO_2	UO_2
N-3F	**M**	**264**	**36**	**53**	**3**	**7**	**3**	**18**	**3.7**	**1.9**	**4.7**	**4.6**	**0.1**	**0.07**	**8.0**	**bdl**	**173**	**5.0**	**0.2**	**0.1**	**4**	**1.8**	**1.1**
	S.D	*73*	*4*	*39*	*0*	*1*	*1*	*3*	*0.4*	*1.2*	*0.9*	*0.4*	*0.1*	0.06	*6.7*	*bdl*	*13*	*0.8*	*0.0*	*0.0*	*2*	*0.2*	*0.2*
N-3 Co	**M**	**316**	**38**	**40**	**589**	**16**	**1006**	**691**	**6.6**	**3.8**	**5.2**	**4.7**	**1.4**	**0.36**	**8.2**	**1.71**	**205**	**4.9**	**0.24**	**0.08**	**235**	**1.8**	**1.2**
	S.D	*41*	*3*	*4*	*153*	*2*	*228*	*366*	*0.4*	*0.5*	*0.7*	*0.4*	*0.5*	*0.12*	*2.0*	*1.12*	*23*	*0.4*	*0.02*	*0.01*	*257*	*0.1*	*0.1*
N-3 Mn	**M**	**267**	**42**	**34**	**8**	**11**	**24**	**81**	**4.4**	**2.4**	**4.9**	**5.0**	**0.5**	**0.13**	**2.0**	**bdl**	**271**	**5.1**	**0.25**	**0.14**	**35**	**1.8**	**1.3**
	S.D	*32*	*0*	*12*	*4*	*2*	*13*	*30*	*0.4*	*1.4*	*0.3*	*0.3*	*0.0*	*0.07*	*1.8*	*bdl*	*39*	*0.3*	*0.02*	*0.001*	*30*	*0.1*	*0.1*

I.3. Mean REE oxides for the cobalt and manganese de/coloured groups. Values as ppm. Group N-3F added for comparison.

Group		Y_2O_3	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Eu Anom	La/Yb	Total REE
N-3F	**M**	**8.29**	**8.37**	**16.20**	**1.98**	**7.63**	**1.53**	**0.37**	**1.31**	**0.21**	**1.29**	**0.27**	**0.77**	**0.12**	**0.85**	**0.13**	0.26	9.79	49.3
	S.D	*0.60*	*0.57*	*1.16*	*0.13*	*0.54*	*0.12*	*0.04*	*0.13*	*0.02*	*0.13*	*0.02*	*0.07*	*0.01*	*0.09*	*0.01*			
N-3 Co	**M**	**8.7**	**8.6**	**16.7**	**2.01**	**7.9**	**1.62**	**0.40**	**1.38**	**0.22**	**1.32**	**0.28**	**0.77**	**0.12**	**0.86**	**0.13**	0.27	9.98	50.9
	S.D	*0.4*	*0.5*	*0.8*	*0.10*	*0.4*	*0.06*	*0.02*	*0.12*	*0.02*	*0.07*	*0.01*	*0.03*	*0.01*	*0.06*	*0.01*			
N-3 Mn	**M**	**9.0**	**9.0**	**17.7**	**2.04**	**7.7**	**1.52**	**0.37**	**1.24**	**0.21**	**1.26**	**0.28**	**0.76**	**0.12**	**0.82**	**0.13**	0.27	11.03	52.2
	S.D	*0.2*	*0.7*	*1.0*	*0.07*	*0.2*	*0.02*	*0.02*	*0.07*	*0.01*	*0.002*	*0.000*	*0.03*	*0.01*	*0.03*	*0.004*			

Appendix J: Plant Ash Glass Analytical Results

J.1. The analytical results for the plant ash glass. The samples are categorised by compositional group in name order. Major and minor elements at wt%, trace elements as ppm.

				Major and minor elements as wt %										
P-1 Tyre Type	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
AY 2844 01	P-1	colourless with brownish tinge	fresh	13.68	3.07	2.00	66.85	0.31	0.88	2.73	8.51	0.09	1.14	0.59
AY 2844 02	P-1	greenish	fresh	12.98	3.15	1.91	66.25	0.29	0.73	2.52	9.68	0.09	1.66	0.60
AY 2844 03	P-1	colourless with greenish tinge	recycled	11.97	2.28	2.24	69.46	0.34	0.83	2.50	8.19	0.10	1.23	0.65
AY 2844 04	P-1	colourless	recycled	13.81	3.33	1.72	65.77	0.32	0.81	3.23	8.66	0.08	1.61	0.51
AY 2844 06	P-1	colourless with yellowish tinge	fresh	13.37	2.63	1.91	66.60	0.35	0.89	2.73	9.17	0.09	1.51	0.58
AY 2989 04	P-1	colourless with greenish tinge	fresh	11.07	2.00	2.08	69.52	0.42	0.82	3.27	8.55	0.09	1.49	0.53
AY 2989 06	P-1	colourless with greenish tinge	recycled	12.81	2.81	1.92	67.56	0.32	0.75	2.55	9.51	0.10	0.94	0.55
AY 2989 07	P-1	colourless with greenish tinge	fresh	14.03	3.85	2.00	66.34	0.37	0.71	3.04	8.29	0.07	0.77	0.40
AY 2989 10	P-1	colourless with greenish tinge	fresh	11.99	2.84	1.90	69.47	0.36	0.84	2.32	8.43	0.09	1.07	0.55
AY 2989 11	P-1	colourless with yellowish tinge	fresh	13.02	2.68	2.03	66.16	0.35	0.71	2.48	10.21	0.11	1.43	0.68
AY 2989 12	P-1	colourless with greenish tinge	recycled	13.16	2.68	1.98	67.21	0.36	0.87	2.54	9.01	0.11	1.25	0.63
AY 2989 13	P-1	light green	recycled	11.61	2.35	2.08	66.70	0.42	0.79	2.88	11.46	0.12	0.75	0.69
AY 2989 14	P-1	colourless	fresh	11.85	2.23	1.79	65.42	0.40	0.78	2.71	12.53	0.10	1.43	0.60
AY 2989 15	P-1	colourless	fresh	10.93	2.77	1.86	68.10	0.42	0.84	2.68	10.35	0.10	1.26	0.54
BSH 2885 01	P-1	pale yellow	fresh	12.36	3.70	1.68	67.33	0.32	0.68	3.16	9.20	0.08	0.88	0.46
BSH 2885 02	P-1	colourless	fresh	10.41	2.76	1.42	73.18	0.23	0.71	2.28	7.80	0.06	0.66	0.34
BSH 2885 04	P-1	colourless	fresh	11.41	3.33	1.60	69.94	0.28	0.67	2.55	9.02	0.07	0.62	0.38
CEA 6194 02	P-1	purple and colourless	fresh	12.97	3.92	1.53	66.57	0.26	0.73	2.82	9.65	0.07	0.96	0.37
CEA 6194 02	P-1	purple and colourless	fresh	12.12	3.79	1.68	66.91	0.29	0.62	2.62	10.23	0.07	1.06	0.45
CEA 6194 03	P-1	‘smokey’ blue	recycled	12.50	3.70	1.75	66.76	0.26	0.70	2.44	10.78	0.07	0.11	0.74
CEA 6194 04	P-1	colourless	recycled	13.01	3.60	1.66	64.42	0.30	0.67	2.63	11.88	0.07	1.07	0.52
CEA 6194 06	P-1	colourless with green tinge	recycled	13.88	3.68	1.62	66.02	0.23	0.77	2.27	9.88	0.07	1.00	0.42
CEA 6194 07	P-1	colourless	fresh	12.84	3.12	1.85	67.45	0.24	0.71	2.18	10.17	0.06	0.85	0.37
CEA 6194 08	P-1	colourless	fresh	14.12	3.13	1.48	65.04	0.32	0.68	2.35	11.11	0.06	1.19	0.35
CEA 6194 09	P-1	‘smokey’ blue	recycled	12.03	4.44	2.07	66.35	0.26	0.66	3.08	10.09	0.06	0.05	0.73

P-1 Tyre Type	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
CEA 6194 11	P-1	colourless	fresh	14.12	3.68	1.71	66.34	0.24	0.81	2.29	9.61	0.06	0.66	0.34
CEA 6194 12	P-1	colourless	fresh	11.83	3.05	2.02	67.28	0.26	0.68	2.52	10.82	0.07	0.84	0.46
CEA 6194 13	P-1	colourless	fresh	12.78	3.69	1.78	66.32	0.27	0.71	2.52	10.34	0.08	0.82	0.54
CEA 6194 14	P-1	colourless	fresh	12.26	3.14	1.81	65.72	0.26	0.64	2.43	12.33	0.06	0.83	0.36
CEA 6194 15	P-1	colourless with purple tinge	fresh	13.36	3.42	1.67	67.32	0.22	0.77	2.01	9.56	0.06	1.11	0.34
HB 3032 07	P-1	colourless with light purple	fresh	12.71	4.23	1.74	66.40	0.23	0.78	2.66	9.94	0.07	0.70	0.38
HB 3032 08	P-1	colourless with light purple	fresh	12.52	4.13	1.75	66.41	0.24	0.75	2.62	10.35	0.07	0.63	0.39
HB 3032 11	P-1	colourless	fresh	12.85	3.35	1.57	67.94	0.26	0.68	2.72	9.21	0.08	0.82	0.40
HB 3032 12	P-1	colourless	fresh	12.41	3.52	1.87	66.26	0.25	0.71	2.51	10.90	0.07	0.90	0.43
HB 3032 13	P-1	light green	recycled	11.10	2.49	1.95	67.68	0.35	0.58	2.57	10.48	0.11	1.89	0.64
HB 3032 14	P-1	colourless	fresh	11.60	2.11	1.83	70.41	0.37	0.88	2.61	7.74	0.11	1.67	0.55
HB 3032 16	P-1	purple swirls,	fresh	13.91	2.78	1.80	67.37	0.30	0.94	2.50	8.46	0.10	1.16	0.53
HB 3032 17	P-1	yellowish-colourless	fresh	13.00	2.81	1.58	68.10	0.32	0.83	2.80	8.97	0.08	0.96	0.41
HB 3032 18	P-1	colourless	fresh	12.64	3.32	1.57	68.17	0.27	0.69	2.74	9.17	0.08	0.83	0.39
HB 3032 19	P-1	green	fresh	10.68	2.45	2.15	72.85	0.34	0.89	1.65	7.67	0.11	0.46	0.63
HB 3032 21	P-1	colourless with light purple	fresh	14.45	2.83	1.58	67.08	0.34	0.84	3.01	8.34	0.08	0.89	0.44
HB 3032 22	P-1	dull light green	recycled	11.46	2.49	1.89	69.54	0.34	0.81	2.41	8.98	0.10	1.22	0.58
HB 3032 23	P-1	colourless	fresh	10.58	3.32	1.67	69.87	0.27	0.76	2.00	10.09	0.09	0.78	0.45
JER 3835 06	P-1	colourless	fresh	11.38	3.41	1.64	70.29	0.22	0.71	1.80	9.58	0.07	0.36	0.39
JER 3835 09	P-1	pale blue	recycled	12.24	2.45	2.03	68.46	0.31	0.74	2.38	9.71	0.10	0.80	0.56
JER 3835 11	P-1	colourless with greenish tinge	fresh	13.49	3.34	1.76	67.37	0.22	0.79	2.11	9.15	0.09	1.04	0.50
JER 3835 15	P-1	colourless	recycled	11.81	3.56	2.05	67.17	0.25	0.63	2.31	10.66	0.07	0.85	0.46
NS 6362 06	P-1	colourless	fresh	12.93	3.20	1.91	66.45	0.23	0.67	2.19	11.02	0.06	0.78	0.38
RAM 3592 04	P-1	colourless	fresh	13.37	3.19	2.10	65.10	0.26	0.79	2.28	10.20	0.10	1.85	0.60
RAM 3592 05	P-1	colourless	fresh	13.45	3.20	2.14	64.83	0.27	0.80	2.30	10.24	0.11	1.90	0.61
RAM 3897 01	P-1	colourless	fresh	12.51	2.79	2.11	68.13	0.34	0.94	2.78	8.10	0.12	1.40	0.62
RAM 3897 02	P-1	colourless	fresh	12.11	2.34	2.15	68.11	0.32	0.91	2.72	8.92	0.09	1.65	0.53
RAM 3897 03	P-1	colourless	fresh	12.09	2.96	1.58	69.85	0.25	0.81	2.86	8.60	0.06	0.49	0.31
RAM 3897 06	P-1	colourless	fresh	12.56	2.57	2.04	69.18	0.25	0.69	2.45	9.15	0.06	0.55	0.36
RAM 3897 07	P-1	colourless	fresh	12.02	2.94	1.58	69.85	0.24	0.81	2.77	8.74	0.06	0.55	0.31
RAM 3897 08	P-1	colourless with greenish tinge	fresh	11.77	2.78	1.79	68.43	0.34	0.93	3.19	9.37	0.09	0.69	0.46
RAM 4740 04	P-1	colourless	fresh	13.73	2.81	1.75	67.89	0.28	0.71	2.18	9.13	0.05	0.98	0.33

P-1 Tyre Type	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
RAM 4740 06	P-1	very pale greenish yellow	fresh	11.93	2.73	1.77	70.10	0.31	0.73	2.40	8.37	0.09	0.91	0.54
RAM 4740 08	P-1	colourless	fresh	9.81	2.92	1.78	70.37	0.32	0.62	2.19	10.47	0.08	0.83	0.46
RAM 4740 10	P-1	colourless	fresh	9.63	2.85	1.73	70.94	0.31	0.61	2.19	10.22	0.08	0.83	0.46
RAM 4768 04	P-1	colourless	fresh	13.17	3.29	1.79	67.77	0.26	0.72	2.61	9.00	0.06	0.76	0.41
RAM 4768 06	P-1	colourless	fresh	13.90	2.70	1.72	68.23	0.28	0.78	2.10	8.56	0.08	1.05	0.48
RAM 4768 11	P-1	colourless	fresh	13.60	2.71	1.68	70.09	0.27	0.82	2.61	6.74	0.08	0.85	0.43
RAM 5947 26	P-1	greenish yellow	fresh	12.01	2.93	2.02	66.25	0.35	0.61	1.97	11.48	0.09	1.52	0.60
RAM 5947 27	P-1	colourless	fresh	12.23	3.07	1.51	69.34	0.26	0.71	2.30	9.33	0.07	0.67	0.38
RAM 5947 28	P-1	pale purple	fresh	12.99	2.71	1.83	69.82	0.24	0.73	2.24	7.69	0.07	1.11	0.45
RAM 5947 30	P-1	colourless	fresh	12.05	2.95	1.58	70.80	0.24	0.73	2.20	8.31	0.06	0.59	0.34
RAM 6297 01	P-1	colourless with greenish tinge	fresh	12.13	3.37	1.79	69.07	0.25	0.76	2.22	8.98	0.08	0.75	0.45
RAM 6297 02	P-1	light greenish blue	recycled	12.27	3.37	1.68	68.55	0.26	0.66	2.30	9.46	0.08	0.72	0.49
RAM 6297 03	P-1	colourless with bluish tinge	recycled	11.58	3.20	2.01	67.62	0.29	0.64	2.30	10.37	0.09	1.15	0.59
RAM 6297 08	P-1	colourless	fresh	12.18	3.02	1.99	69.90	0.23	0.81	2.05	7.67	0.11	1.25	0.67
RAM 6297 09	P-1	light greenish blue	recycled	11.69	2.45	2.21	68.53	0.40	0.83	2.51	9.85	0.12	0.51	0.75
RAM 6297 10	P-1	light greenish blue	fresh	12.08	2.27	1.97	69.70	0.36	0.88	2.61	7.87	0.10	1.41	0.59
RAM 6297 11	P-1	green	fresh	12.23	2.92	2.21	69.45	0.34	0.87	2.38	7.26	0.13	1.32	0.76
RAM 6297 12	P-1	colourless with greenish tinge	fresh	10.64	3.19	1.87	68.85	0.28	0.58	2.35	10.36	0.07	1.19	0.47
RAM 6297 13	P-1	green	fresh	12.25	3.00	2.25	69.02	0.34	0.88	2.39	7.35	0.13	1.48	0.76
RAM 6297 14	P-1	light olive green	fresh	11.62	2.32	2.09	68.97	0.40	0.84	2.51	9.82	0.11	0.49	0.68
RAM 6297 15	P-1	light greenish blue	recycled	11.57	2.55	2.06	67.78	0.39	0.77	3.31	10.14	0.11	0.51	0.67
RAM 6297 16	P-1	colourless	recycled	11.52	2.46	2.28	70.36	0.35	0.87	2.11	7.41	0.12	1.61	0.76
RAM 6490 05	P-1	colourless with yellowish tinge	fresh	11.95	3.52	1.89	67.33	0.26	0.64	2.43	10.35	0.07	0.92	0.46
RAM 6490 06	P-1	light green	recycled	12.33	3.46	2.03	66.06	0.28	0.67	2.81	10.45	0.07	1.15	0.51
SEP 3791 13	P-1	pale greenish-blue	recycled	11.78	3.47	2.06	65.91	0.38	0.56	2.27	11.95	0.09	0.70	0.63
SEP 3791 15	P-1	pale greenish-blue	fresh	11.22	3.38	1.55	69.80	0.26	0.71	2.34	9.71	0.06	0.50	0.32
TIB 5583 08	P-1	colourless	fresh	13.43	3.42	1.67	66.76	0.24	0.73	2.75	9.63	0.08	0.76	0.40
TIB 5583 09	P-1	colourless	fresh	11.27	2.05	2.20	68.74	0.39	0.90	3.34	8.29	0.10	1.99	0.57
TIB 5583 11	P-1	purple	fresh	11.33	1.83	2.04	69.38	0.45	1.01	3.40	8.62	0.11	1.09	0.57
TIB 5583 12	P-1	colourless	fresh	12.62	3.09	1.61	68.18	0.24	0.73	2.38	9.61	0.07	0.95	0.38
TIB 5583 13	P-1	colourless	fresh	11.87	2.43	1.97	68.05	0.38	0.91	3.18	9.23	0.10	1.19	0.54
TIB 5583 15	P-1	light green	fresh	10.90	2.50	1.94	67.51	0.44	0.93	2.35	11.18	0.10	1.37	0.57

P-1 Tyre Type	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
TIB 5583 16	P-1	colourless	fresh	13.00	2.54	1.81	67.99	0.32	1.01	3.06	8.76	0.09	0.81	0.47
TIB 5583 17	P-1	colourless	fresh	12.02	3.04	2.19	68.49	0.31	0.92	2.23	8.73	0.11	1.19	0.64
TIB 5583 18	P-1	colourless	fresh	13.52	3.86	1.80	66.36	0.27	0.74	2.81	9.41	0.08	0.57	0.43
TIB 5583 19	P-1	colourless	fresh	13.05	3.09	1.77	66.86	0.27	0.74	2.35	10.46	0.08	0.73	0.46
TIB 5583 22	P-1	colourless	fresh	13.03	3.18	1.82	67.77	0.21	0.82	2.24	9.26	0.09	0.99	0.45
TIB 5583 23	P-1	colourless with green tinge	fresh	10.85	3.11	1.93	68.07	0.27	0.64	2.40	10.85	0.08	1.19	0.46
TIB 5583 24	P-1	colourless	fresh	13.97	3.80	2.02	65.11	0.28	0.72	2.82	9.44	0.08	1.16	0.45
TIB 5583 25	P-1	colourless	fresh	15.78	3.06	1.81	65.11	0.25	0.87	2.36	9.18	0.09	0.92	0.45
TIB 5583 26	P-1	colourless	fresh	12.34	2.82	1.72	67.84	0.26	0.88	2.85	9.91	0.08	0.75	0.38
TIB 5583 27	P-1	colourless	fresh	13.91	2.63	1.92	67.25	0.29	1.06	2.99	8.16	0.10	1.06	0.50
TIB 5583 28	P-1	colourless	fresh	11.69	2.65	2.02	66.83	0.40	0.91	3.06	10.62	0.10	1.00	0.55
TIB 5583 29	P-1	colourless	fresh	14.07	2.56	2.03	68.05	0.35	1.06	2.76	7.41	0.10	0.88	0.58
TIB 5583 30	P-1	colourless	fresh	10.37	3.26	1.87	69.00	0.24	0.75	2.01	10.69	0.08	1.11	0.47
P-2 Syro-Palestine Type	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
BSH 2885 03	P-2a	colourless	fresh	14.26	3.41	0.87	67.66	0.34	0.80	2.12	9.87	0.07	0.08	0.41
HB 3032 04	P-2a	green	fresh	13.59	2.93	0.72	69.29	0.32	0.71	2.18	9.72	0.06	0.03	0.34
RAM 4740 05	P-2a	colourless	fresh	13.34	3.06	0.97	68.45	0.38	0.88	2.57	8.55	0.07	1.20	0.38
SEP 3791 16	P-2a	very pale greenish-blue	fresh	11.95	3.17	1.01	68.78	0.37	0.60	2.22	11.17	0.08	0.05	0.44
TIB 5583 14	P-2a	light blueish green	fresh	15.03	3.39	0.77	66.16	0.32	0.90	2.65	10.15	0.06	0.10	0.32
TIB 5583 20	P-2a	light blueish green	fresh	14.52	3.85	0.80	66.31	0.31	0.85	2.40	10.33	0.06	0.03	0.36
BSH 2885 05	P-2b	very pale green	fresh	9.60	3.38	1.03	70.98	0.31	0.79	2.09	9.99	0.11	0.97	0.52
BSH 2885 07	P-2b	colourless	fresh	10.85	3.08	1.01	72.49	0.41	0.73	2.43	7.59	0.11	0.65	0.50
BSH 2885 08	P-2b	colourless	fresh	12.61	3.72	0.83	69.90	0.26	0.66	1.81	9.14	0.10	0.40	0.42
BSH 2885 11	P-2b	very pale blue	fresh	12.50	3.79	0.82	69.98	0.25	0.64	1.74	9.21	0.10	0.41	0.41
BSH 2885 12	P-2b	colourless	fresh	9.82	3.04	1.05	72.16	0.38	0.74	2.51	8.64	0.13	0.82	0.53
P-3 Nishapur Colourless	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
CEA 6194 10	P-3	‘smokey’ blue	recycled?	11.67	4.95	1.27	71.23	0.10	0.58	2.30	6.66	0.05	0.51	0.53
HB 3032 09	P-3	colourless	fresh	14.26	6.17	0.62	70.72	0.12	0.62	2.93	3.96	0.03	0.30	0.17
HB 3032 15	P-3	colourless	fresh	12.42	5.00	1.07	71.29	0.08	0.65	2.38	6.34	0.04	0.35	0.27
JER 5124 31	P-3	yellowish green	fresh	10.56	4.98	1.01	73.11	0.08	0.52	2.20	6.38	0.05	0.66	0.35

P-3 Nishapur Colourless	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
RAM 3592 06	P-3	colourless	fresh	12.65	4.84	1.08	69.03	0.14	0.72	3.09	7.58	0.03	0.51	0.23
RAM 3897 04	P-3	colourless	fresh	13.10	5.39	0.83	70.18	0.10	0.71	2.96	6.09	0.05	0.25	0.23
RAM 4740 02	P-3	colourless	fresh	11.15	4.82	1.03	73.35	0.09	0.53	2.12	6.18	0.03	0.34	0.27
RAM 4740 12	P-3	colourless	fresh	13.31	4.71	1.11	71.49	0.10	0.63	2.08	5.84	0.05	0.22	0.36
RAM 4740 13	P-3	colourless	fresh	10.59	5.10	1.02	73.43	0.08	0.49	1.90	6.56	0.04	0.40	0.29
RAM 4768 05	P-3	colourless	fresh	10.55	4.66	0.94	74.16	0.10	0.62	2.32	5.87	0.03	0.43	0.23
RAM 4768 10	P-3	colourless	fresh	12.24	4.06	0.81	72.82	0.10	0.58	2.79	5.86	0.04	0.37	0.24
RAM 5947 29	P-3	colourless	fresh	12.02	4.74	1.00	72.76	0.08	0.57	2.13	5.95	0.03	0.35	0.29
RAM 5947 31	P-3	colourless	fresh	11.73	5.16	1.02	71.36	0.12	0.56	2.42	6.74	0.03	0.47	0.28
RAM 6297 07	P-3	colourless	fresh	13.23	5.47	0.82	69.66	0.12	0.69	3.24	6.27	0.02	0.21	0.17
RAM 6490 11	P-3	colourless	fresh	14.07	5.13	1.21	69.30	0.12	0.56	2.80	5.45	0.07	0.79	0.36
RAM 6490 12	P-3	colourless	fresh	11.61	5.27	0.91	71.99	0.09	0.64	2.34	6.51	0.03	0.30	0.23
SEP 3791 14	P-3	colourless	fresh	15.37	6.11	1.42	68.44	0.11	0.57	1.89	4.49	0.07	0.98	0.40
TIB 5583 21	P-3	colourless	fresh	12.86	5.15	0.97	70.21	0.09	0.77	2.76	6.30	0.04	0.47	0.28
P-4 Nishapur Coloured	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
CEA W2S3 04	P-4	cobalt blue	-	13.65	3.98	2.82	65.46	0.20	0.57	3.02	5.79	0.11	1.39	2.30
JER 3835 07	P-4	cobalt blue	-	11.86	2.98	2.85	68.81	0.19	0.81	1.48	6.04	0.16	1.12	2.79
RAM 3897 05	P-4	cobalt blue	-	14.42	2.73	1.83	65.00	0.23	0.62	2.25	9.60	0.13	1.03	1.60
RAM 4768 08	P-4	cobalt blue	-	13.42	2.72	2.33	68.47	0.22	0.71	2.15	6.35	0.14	1.11	1.85
RAM 4768 09	P-4	cobalt blue	-	12.39	2.52	2.20	69.25	0.28	0.78	1.65	8.25	0.16	0.74	1.37
RAM 6297 05	P-4	cobalt blue	-	11.73	3.12	3.09	67.88	0.19	0.74	1.59	5.65	0.20	1.26	3.43
RAM 6490 07	P-4	cobalt blue	-	13.58	3.27	1.91	65.52	0.23	0.76	1.57	7.26	0.10	2.11	2.89
RAM 6490 08	P-4	cobalt blue	-	11.94	2.70	2.13	68.35	0.19	0.73	1.77	5.89	0.14	2.04	2.94
RAM 6490 09	P-4	cobalt blue	-	12.90	2.70	2.42	67.48	0.19	0.79	2.30	6.52	0.16	1.37	2.22
TIB 5583 07	P-4	cobalt blue	-	14.61	2.71	2.08	66.61	0.17	0.72	2.47	6.66	0.13	0.32	2.54
Outliers	**Group**	**Colour**	**Recycled**	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**Fe_2O_3**
AY 2989 08	Raqqa 4?	light green	-	15.77	4.72	3.16	65.23	0.13	0.63	3.36	6.08	0.09	0.16	0.51
BSH 2885 09	P-2b	amber	-	11.67	3.52	0.66	70.81	0.40	0.78	3.58	8.00	0.09	0.03	0.36
BSH 2885 10	P-2b	very pale blue	-	11.57	3.02	0.55	71.75	0.32	0.75	3.18	8.07	0.09	0.29	0.28
CEA 6194 01	unknown	light green	-	14.06	3.50	1.33	66.34	0.30	0.72	2.41	9.69	0.09	0.77	0.56

Outliers	Group	Colour	Recycled	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3
CEA 6194 05	unknown	light green	-	12.94	2.87	2.14	67.67	0.28	0.75	1.83	9.58	0.15	0.70	0.87
HB 3032 06	P-1 Co	blue	-	12.70	2.97	1.14	67.56	0.37	0.74	2.53	9.84	0.09	0.46	1.23
HB 3032 20	P-1	colourless	-	12.20	3.12	1.54	67.40	0.42	0.72	2.37	10.72	0.10	0.61	0.60
RAM 5947 17	P-3	greenish yellow	-	13.97	4.44	1.75	69.34	0.20	0.63	2.84	4.58	0.09	1.40	0.62
TR 6055 02	Raqqa 4?	yellowish	-	12.77	4.25	3.12	63.33	0.39	0.80	1.88	10.83	0.18	1.08	1.14

	Trace elements as ppm																
P-1 Tyre Type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
AY 2844 01	11.0	280	25	16	4.7	11.6	48	35	4.3	2.0	15.9	612	8.1	46	2.1	3.2	bdl	0.07
AY 2844 02	11.6	301	25	17	6.4	13.3	64	32	4.3	1.8	16.5	491	7.8	48	2.2	4.6	0.09	bdl
AY 2844 03	9.7	236	24	15	6.0	12.1	460	43	4.4	3.6	13.9	684	8.1	52	2.2	2.7	0.76	0.06
AY 2844 04	12.5	324	23	15	10.2	10.7	90	46	4.2	1.5	16.5	468	7.6	48	1.9	4.9	bdl	bdl
AY 2844 06	9.2	310	27	18	6.3	13.5	66	47	4.3	1.5	15.9	801	7.8	51	2.2	4.3	0.05	bdl
AY 2989 04	7.2	210	25	n/a	6.1	11.5	30	37	3.6	5.3	16.7	734	8.7	54	2.2	4.2	bdl	bdl
AY 2989 06	8.9	255	24	n/a	5.5	11.3	125	41	3.1	5.1	16.1	595	8.2	57	2.3	3.3	5.97	0.07
AY 2989 07	9.2	382	19	n/a	2.9	8.7	42	35	3.1	4.1	19.1	466	9.6	48	1.8	2.5	0.08	0.07
AY 2989 10	5.0	247	23	n/a	4.1	11.5	33	33	3.2	3.7	14.2	590	8.1	54	2.2	2.8	0.05	bdl
AY 2989 11	8.2	263	33	n/a	5.5	14.4	59	39	3.7	3.9	17.8	523	10.6	60	2.7	5.0	bdl	0.05
AY 2989 12	6.5	269	28	n/a	6.9	12.7	142	47	3.4	4.6	15.8	653	9.0	59	2.6	4.0	0.18	0.06
AY 2989 13	5.4	200	28	n/a	4.9	12.8	28	39	3.4	3.7	15.2	740	9.8	61	2.8	2.2	0.05	0.07
AY 2989 14	3.3	199	26	n/a	5.8	11.4	19	40	3.2	4.6	13.1	726	8.7	56	2.5	3.5	bdl	0.07
AY 2989 15	4.6	210	27	n/a	4.8	11.6	51	36	3.2	4.0	15.0	836	9.5	58	2.4	3.3	bdl	bdl
BSH 2885 01	bdl	280	19	79	2.6	9.9	35	39	4.1	2.8	19.1	683	5.7	42	1.9	3.2	bdl	bdl
BSH 2885 02	bdl	228	16	18	2.2	7.8	25	35	3.8	3.0	16.9	646	5.6	36	1.5	2.5	bdl	0.10
BSH 2885 04	bdl	274	17	15	2.7	8.9	22	37	3.5	2.9	17.3	683	5.8	40	1.5	2.4	bdl	bdl

P-1 Tyre Type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
CEA 6194 02	16.8	304	18	12	3.0	8.9	45	36	3.0	2.2	15.2	758	5.8	41	1.7	3.2	bdl	bdl
CEA 6194 02	16.3	288	21	15	4.4	10.2	51	39	3.1	2.5	16.4	703	7.0	46	1.9	3.9	0.09	bdl
CEA 6194 03	14.7	243	15	13	50.8	9.6	92	48	3.1	3.2	17.9	800	6.8	40	1.7	1.5	0.06	bdl
CEA 6194 04	16.3	318	22	16	11.4	11.5	63	44	3.1	2.9	16.6	731	7.8	47	1.7	3.8	0.07	bdl
CEA 6194 06	13.8	268	18	13	9.5	8.0	49	34	3.0	2.7	15.3	698	6.0	44	1.7	3.4	0.05	0.05
CEA 6194 07	14.5	251	16	12	3.2	8.7	27	52	3.1	3.1	17.4	755	6.9	40	1.6	1.8	0.05	bdl
CEA 6194 08	14.6	278	18	13	6.9	9.3	74	43	2.8	2.7	19.2	779	6.4	42	1.6	4.0	0.07	bdl
CEA 6194 09	15.2	259	16	13	59.3	8.7	101	44	3.6	4.3	21.1	825	8.2	39	1.7	1.4	0.06	0.05
CEA 6194 11	14.1	259	15	11	2.4	7.1	26	29	2.9	2.3	15.9	707	6.3	39	1.5	2.6	bdl	bdl
CEA 6194 12	15.0	285	18	17	3.4	10.6	16	94	3.5	3.9	21.4	785	7.7	42	1.7	1.2	0.08	bdl
CEA 6194 13	14.7	260	20	18	5.2	9.8	47	37	3.2	2.7	16.1	760	6.8	46	1.9	3.3	0.09	0.07
CEA 6194 14	12.1	236	17	13	3.2	7.9	40	29	3.1	3.4	19.9	829	8.7	38	1.5	3.1	bdl	bdl
CEA 6194 15	14.0	261	17	14	3.5	8.2	39	35	3.1	2.4	16.1	754	6.8	40	1.6	3.3	0.05	0.05
HB 3032 07	15.5	246	17	15	3.0	7.8	34	32	3.0	2.6	16.8	911	6.9	43	1.7	3.1	bdl	0.07
HB 3032 08	15.2	239	18	16	2.9	7.9	30	32	3.1	2.6	16.5	884	7.1	43	1.7	3.2	bdl	bdl
HB 3032 11	12.2	263	18	15	3.9	7.1	57	30	2.8	2.6	18.1	512	7.3	46	1.8	2.6	bdl	bdl
HB 3032 12	14.2	269	21	18	4.5	9.7	50	36	3.3	3.5	19.4	888	8.7	42	1.8	3.4	0.07	bdl
HB 3032 13	13.8	231	34	26	7.9	14.2	86	45	4.0	3.6	20.0	557	9.9	58	2.6	6.7	0.09	0.09
HB 3032 14	9.9	190	23	16	6.0	10.8	16	37	3.6	3.4	13.0	622	8.0	54	2.4	2.5	bdl	0.07
HB 3032 16	12.2	228	24	16	5.5	8.9	70	33	3.3	2.7	14.4	617	7.4	50	2.3	2.9	bdl	bdl
HB 3032 17	12.5	314	21	17	3.4	11.1	42	45	2.9	2.4	19.7	665	7.8	46	1.9	3.4	bdl	bdl
HB 3032 18	12.6	268	18	13	3.8	6.9	59	31	2.7	2.8	17.8	513	7.3	46	1.8	2.7	0.13	bdl
HB 3032 19	11.6	204	24	18	3.4	9.8	21	37	3.5	2.0	11.2	406	7.4	55	2.7	2.3	bdl	0.07
HB 3032 21	13.5	289	20	14	3.3	8.6	31	33	2.9	2.3	17.2	501	7.7	47	1.9	3.2	0.08	bdl
HB 3032 22	11.2	213	26	16	5.4	10.7	46	40	3.5	3.4	13.4	683	8.0	54	2.4	3.0	0.08	0.06
HB 3032 23	11.7	216	21	12	3.3	7.7	37	28	3.0	2.0	15.3	506	7.7	50	2.1	2.6	bdl	bdl
JER 3835 06	12.9	273	16	31	2.0	9.2	18	35	2.9	2.1	15.6	729	7.4	47	1.9	2.0	0.09	bdl

P-1 Tyre Type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
JER 3835 09	10.0	253	22	n/a	8.4	11.4	157	49	3.7	3.7	15.2	698	8.2	61	2.3	2.5	0.23	bdl
JER 3835 11	8.5	247	22	n/a	3.8	9.9	45	27	3.4	3.0	15.7	588	7.3	51	2.2	3.5	bdl	bdl
JER 3835 15	12.4	262	18	n/a	4.2	10.3	81	61	3.6	3.8	20.3	781	10.4	45	1.9	1.5	0.06	bdl
NS 6362 06	16.7	252	16	17	2.8	8.7	26	40	3.3	3.4	19.1	847	7.2	39	1.6	2.1	bdl	0.05
RAM 3592 04	13.6	258	31	23	6.7	12.6	62	36	3.9	7.4	17.9	581	7.9	53	2.5	5.9	0.06	0.05
RAM 3592 05	13.3	261	32	23	5.9	12.8	62	37	4.1	3.8	18.0	583	8.1	53	2.6	6.1	0.06	0.06
RAM 3897 01	11.5	260	25	19	5.8	11.5	16	41	3.9	3.2	15.4	684	8.2	57	2.6	2.2	bdl	0.05
RAM 3897 02	12.0	231	26	17	5.1	11.2	16	37	4.0	4.1	16.2	687	9.4	49	2.1	3.7	bdl	0.08
RAM 3897 03	13.8	272	14	13	2.1	6.4	23	36	2.7	2.0	16.6	597	7.0	43	1.5	1.9	bdl	0.07
RAM 3897 06	12.9	218	15	15	2.3	7.4	18	53	3.2	3.3	19.8	657	9.3	40	1.6	1.8	bdl	bdl
RAM 3897 07	14.1	265	14	13	2.1	6.8	23	37	2.6	2.1	16.6	620	7.0	42	1.5	2.4	bdl	0.08
RAM 3897 08	11.6	236	20	16	3.3	9.8	37	41	3.1	3.0	16.2	1003	8.2	49	1.9	1.8	bdl	bdl
RAM 4740 04	7.9	239	14	54	3.2	8.9	15	66	3.7	3.5	17.8	709	5.7	32	1.3	0.8	bdl	bdl
RAM 4740 06	bdl	249	22	18	5.0	10.2	40	29	3.4	3.7	17.6	529	8.3	48	2.1	2.7	bdl	bdl
RAM 4740 08	bdl	219	21	19	3.7	10.7	37	37	3.6	3.9	17.2	731	7.8	48	2.0	3.2	0.18	0.06
RAM 4740 10	bdl	220	21	19	3.7	10.7	38	40	3.7	3.8	18.0	716	7.4	45	1.8	3.2	0.18	0.06
RAM 4768 04	bdl	283	14	56	2.6	7.7	14	77	4.1	3.9	19.2	728	7.0	35	1.4	1.0	bdl	0.11
RAM 4768 06	bdl	223	21	29	3.7	8.8	39	24	4.8	3.0	14.8	467	6.1	43	2.0	3.3	0.21	bdl
RAM 4768 11	bdl	235	19	16	3.1	7.9	35	30	4.5	2.9	17.3	437	6.2	41	1.8	3.7	bdl	0.08
RAM 5947 26	5.3	248	31	67	4.5	14.3	62	36	5.4	3.9	19.5	636	9.8	54	2.4	5.6	bdl	0.05
RAM 5947 27	8.0	253	18	129	2.7	10.1	37	39	2.8	3.2	18.2	715	6.6	39	1.6	2.7	bdl	0.13
RAM 5947 28	bdl	251	22	22	4.0	9.6	38	24	3.9	3.9	19.5	500	6.9	40	1.7	3.6	bdl	0.11
RAM 5947 30	6.6	249	15	33	2.0	8.8	22	42	3.2	3.3	17.8	696	6.4	42	1.6	2.5	bdl	0.13
RAM 6297 01	11.8	263	18	15	2.6	10.0	32	33	3.4	1.8	15.7	596	6.3	46	1.9	2.6	bdl	bdl
RAM 6297 02	15.3	278	19	19	14.7	12.5	59	45	3.2	2.6	17.0	661	7.1	53	1.8	2.5	0.12	bdl
RAM 6297 03	14.0	253	24	21	6.7	13.1	62	38	4.0	2.9	17.0	574	8.1	56	2.3	3.8	1.71	0.05
RAM 6297 08	11.9	268	27	20	5.0	12.6	49	30	4.2	2.7	16.1	438	9.4	57	2.6	3.8	0.06	bdl

P-1 Tyre Type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
RAM 6297 09	10.9	217	26	23	4.3	12.6	20	37	4.0	2.3	14.5	681	9.1	59	2.8	1.5	0.06	bdl
RAM 6297 10	8.5	210	22	15	5.5	10.4	16	37	4.0	2.9	13.2	636	7.9	53	2.3	2.1	bdl	bdl
RAM 6297 11	9.1	265	27	18	6.0	13.2	17	47	4.5	2.5	14.1	541	7.4	56	2.8	2.4	bdl	bdl
RAM 6297 12	12.0	278	22	16	3.6	12.8	46	48	3.8	1.8	18.7	671	7.8	45	1.8	4.2	0.06	bdl
RAM 6297 13	9.3	265	28	16	6.3	13.6	17	41	4.6	2.7	14.4	555	7.7	58	2.8	2.5	bdl	bdl
RAM 6297 14	9.2	210	24	17	3.9	11.1	18	34	3.8	2.0	13.9	658	8.8	58	2.6	1.5	bdl	bdl
RAM 6297 15	10.3	218	23	17	4.1	11.5	21	36	3.8	2.3	16.4	728	8.7	54	2.5	1.4	0.05	bdl
RAM 6297 16	8.7	216	31	13	6.7	13.3	33	36	4.6	2.8	11.1	592	7.9	55	2.7	2.7	0.11	bdl
RAM 6490 05	15.7	279	20	n/a	4.1	10.9	47	40	3.5	3.0	19.9	792	7.8	45	1.8	3.6	0.08	bdl
RAM 6490 06	16.0	296	19	n/a	23.7	11.9	76	82	4.0	2.7	20.4	820	7.9	45	1.8	1.5	0.19	bdl
SEP 3791 13	bdl	261	26	25	18.1	16.3	83	66	3.9	6.1	17.7	793	8.5	54	2.1	1.8	0.41	bdl
SEP 3791 15	bdl	233	20	13	0.8	6.1	20	33	3.0	3.0	15.7	818	6.8	40	1.6	1.9	bdl	bdl
TIB 5583 08	11.8	294	18	12	3.8	7.3	58	32	3.2	2.8	19.3	524	7.5	45	1.8	2.6	0.06	bdl
TIB 5583 09	9.3	221	26	16	9.0	11.8	43	44	4.6	5.0	16.9	749	8.7	52	2.2	3.6	0.06	0.07
TIB 5583 11	10.4	222	23	13	5.7	9.0	56	45	4.0	3.7	15.0	929	8.1	57	2.4	1.2	bdl	bdl
TIB 5583 12	11.2	277	19	12	4.3	7.9	37	29	3.2	2.6	16.8	556	7.3	44	1.7	2.7	bdl	bdl
TIB 5583 13	9.0	231	23	16	5.1	10.3	17	43	3.8	3.5	15.4	802	7.8	53	2.2	2.9	bdl	0.05
TIB 5583 15	9.5	259	28	18	5.3	11.1	51	40	4.0	4.0	10.7	1152	9.0	56	2.3	3.8	bdl	bdl
TIB 5583 16	13.3	281	20	16	4.7	9.0	34	38	3.3	3.1	17.6	765	8.2	49	2.0	1.9	bdl	0.06
TIB 5583 17	14.8	249	27	23	4.8	12.1	45	39	4.2	2.6	13.6	463	8.1	55	2.6	3.4	bdl	0.05
TIB 5583 18	13.7	333	18	16	2.5	9.1	25	44	3.0	1.8	19.3	611	6.1	47	2.0	2.4	bdl	bdl
TIB 5583 19	14.7	264	20	18	3.8	10.2	27	34	3.2	2.6	18.1	635	8.0	47	2.0	2.7	bdl	bdl
TIB 5583 22	13.9	257	20	18	3.4	9.3	45	30	3.5	2.8	16.1	569	6.9	47	2.0	3.5	bdl	bdl
TIB 5583 23	15.4	283	23	21	3.9	12.6	48	52	3.6	2.6	19.4	665	8.3	47	1.9	4.5	bdl	bdl
TIB 5583 24	14.3	335	22	18	3.3	10.3	39	35	3.7	3.2	19.2	550	8.4	44	1.9	4.0	0.06	bdl
TIB 5583 25	12.7	249	21	16	3.6	8.7	37	30	3.2	2.1	16.6	533	6.7	47	2.0	3.2	bdl	bdl
TIB 5583 26	15.5	292	16	16	3.4	9.4	28	50	3.0	2.3	16.8	857	7.6	44	1.7	2.8	bdl	bdl

P-1 Tyre Type	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
TIB 5583 27	11.9	284	25	16	5.4	11.0	22	31	3.4	2.6	15.7	625	7.2	50	2.2	4.6	bdl	bdl
TIB 5583 28	14.1	284	22	18	5.5	10.5	64	46	3.6	2.6	14.6	788	8.1	56	2.3	2.4	bdl	bdl
TIB 5583 29	10.9	290	23	16	3.7	10.0	33	38	3.6	2.4	15.3	575	8.0	61	2.3	1.7	bdl	bdl
TIB 5583 30	14.3	276	23	18	3.5	11.6	54	43	3.5	2.4	16.2	740	8.2	49	2.1	4.5	bdl	0.06
P-2 Syro-Palestine Type	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
BSH 2885 03	bdl	285	18	26	2.9	14.2	19	36	1.9	2.5	10.1	626	4.9	46	1.6	0.9	bdl	0.10
HB 3032 04	17.3	315	19	18	1.7	17.4	32	41	1.5	1.7	11.0	609	5.5	48	1.3	0.8	0.08	bdl
RAM 4740 05	15.4	350	28	28	5.3	17.6	29	62	2.4	3.6	11.8	589	5.9	136	1.9	6.2	bdl	0.08
SEP 3791 16	bdl	296	20	24	5.2	13.5	49	52	1.5	4.1	12.0	749	5.4	88	1.8	1.0	0.37	bdl
TIB 5583 14	14.4	403	15	18	1.8	11.7	29	47	1.7	1.1	14.4	645	4.4	43	1.4	0.9	0.06	bdl
TIB 5583 20	22.1	430	21	18	2.4	22.2	20	52	1.6	1.7	11.0	749	5.3	58	1.4	0.8	0.06	bdl
BSH 2885 05	bdl	287	21	19	24.9	9.6	232	117	3.9	3.6	11.0	648	4.8	150	2.4	1.4	0.08	0.37
BSH 2885 07	bdl	319	21	19	15.2	6.9	156	90	3.0	2.7	10.6	441	4.5	125	2.2	1.2	0.07	0.22
BSH 2885 08	bdl	320	15	16	11.5	5.7	103	45	2.4	2.6	12.4	494	5.3	152	2.6	0.8	0.05	0.05
BSH 2885 11	bdl	314	15	14	11.6	4.4	97	41	2.5	2.0	11.7	503	5.3	151	2.6	0.9	bdl	0.13
BSH 2885 12	bdl	274	20	18	20.1	9.5	199	102	3.4	3.2	12.2	529	4.8	189	2.8	1.0	0.08	0.42
P-3 Nishapur Colourless	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
CEA 6194 10	48.7	209	16	35	54.7	34.9	183	54	2.5	3.3	16.1	429	3.9	48	1.4	1.9	0.19	bdl
HB 3032 09	58.0	228	13	59	2.1	8.7	9	21	1.2	0.9	13.7	456	2.4	32	0.7	1.7	bdl	bdl
HB 3032 15	47.5	209	12	25	2.4	12.0	9	16	2.1	1.2	16.2	430	3.9	63	1.4	2.1	bdl	bdl
JER 5124 31	44.5	167	15		4.7	15.1	15	23	2.0	1.6	14.8	446	4.1	60	1.5	2.8	bdl	bdl
RAM 3592 06	40.8	213	9	19	1.8	12.1	10	26	2.2	1.1	16.3	449	3.4	31	1.2	1.0	bdl	bdl
RAM 3897 04	55.7	232	10	18	1.8	11.1	13	23	1.8	1.1	17.6	522	4.5	90	1.3	0.9	bdl	bdl
RAM 4740 02	33.8	171	10	23	2.4	12.6	9	20	2.4	1.7	15.6	432	3.3	36	1.0	0.9	bdl	bdl
RAM 4740 12	37.8	223	14	35	2.2	16.3	8	17	2.0	1.8	15.2	377	3.6	50	1.3	1.7	bdl	bdl

P-3 Nishapur Colourless	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
RAM 4740 13	25.5	167	12	21	3.1	11.8	7	19	2.1	2.0	14.2	462	3.5	44	1.2	1.3	bdl	bdl
RAM 4768 05	19.6	185	9	19	2.1	11.0	7	14	2.9	1.6	14.9	401	3.1	36	1.0	1.0	bdl	0.11
RAM 4768 10	16.2	204	9	23	1.3	11.0	11	18	2.6	2.0	15.6	447	3.0	58	1.0	1.7	bdl	0.12
RAM 5947 29	33.8	188	10	26	2.4	13.9	7	20	2.4	1.8	16.5	390	3.2	37	1.1	1.0	bdl	bdl
RAM 5947 31	30.0	194	14	187	3.3	13.9	17	16	2.6	1.8	16.5	495	3.2	34	1.0	1.9	bdl	0.07
RAM 6297 07	52.4	213	8	11	1.9	10.2	11	21	1.7	0.3	17.9	479	2.9	32	0.7	1.0	bdl	bdl
RAM 6490 11	52.1	263	19	81	5.1	16.1	15	19	2.9	1.5	14.6	498	5.5	162	2.0	3.8	bdl	0.07
RAM 6490 12	45.8	200	9	15	2.1	11.8	9	18	1.8	0.9	15.9	460	3.4	41	1.0	1.0	bdl	bdl
SEP 3791 14	35.2	230	37	52	4.7	14.9	11	19	3.7	2.5	12.5	529	5.4	125	1.8	2.4	0.11	bdl
TIB 5583 21	48.6	249	9	19	2.3	10.5	8	23	1.9	1.4	16.7	374	3.5	49	1.2	1.4	bdl	bdl
P-4 Nishapur Coloured	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
CEA W2S3 04	33.1	382	27	61	540.4	276.6	3591	222	7.0	18.4	19.2	541	5.9	99	2.4	2.6	0.81	bdl
JER 3835 07	58.7	435	39	61	1283.8	310.5	4732	798	9.3	19.5	7.9	642	9.2	169	3.9	4.3	0.52	bdl
RAM 3897 05	60.3	453	31	148	1060.0	138.9	1907	508	5.5	18.4	10.4	745	7.0	127	2.9	4.6	0.38	0.07
RAM 4768 08	18.3	522	39	105	699.4	55.1	2176	673	8.3	11.4	11.3	354	7.5	141	3.5	5.0	0.31	0.47
RAM 4768 09	bdl	312	30	54	510.5	172.6	1677	294	6.0	12.2	11.0	484	7.5	135	3.1	3.3	0.33	0.19
RAM 6297 05	67.4	436	44	103	1594.1	363.3	6093	1113	10.1	33.0	9.8	430	9.2	281	4.6	5.4	0.91	0.01
RAM 6490 07	60.1	557	66	n/a	1904.0	414.9	3877	376	7.0	26.3	6.4	343	6.6	30	2.3	10.5	0.32	0.11
RAM 6490 08	49.7	478	42	n/a	1941.7	834.2	6388	802	9.4	47.3	9.9	474	6.9	146	3.4	7.0	0.98	0.09
RAM 6490 09	60.4	499	42	203	1104.2	58.9	4600	1658	10.3	24.3	12.8	365	8.2	152	4.0	9.7	0.87	0.09
TIB 5583 07	64.0	603	33	112	1936.1	106.9	4825	957	8.4	10.3	14.0	427	7.0	143	2.9	3.7	0.25	0.06
Outliers	**Li_2O**	**B_2O_3**	**V_2O_5**	**Cr_2O_3**	**CoO**	**NiO**	**CuO**	**ZnO**	**GaO**	**As_2O_3**	**Rb_2O**	**SrO**	**Y_2O_3**	**ZrO_2**	**Nb_2O_3**	**MoO**	**Ag**	**Cd**
AY 2989 08	48.4	262	24	n/a	3.4	13.6	15	26	4.7	2.6	31.7	749	5.6	83	2.1	1.0	0.05	bdl
BSH 2885 09	bdl	334	11	49	1.4	4.8	11	46	1.4	1.4	10.4	383	4.8	155	2.2	1.0	0.26	bdl
BSH 2885 10	bdl	259	10	19	7.4	3.9	86	54	1.6	2.0	8.9	427	4.8	176	2.2	0.7	0.07	bdl

Outliers	Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	CuO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd
CEA 6194 01	29.4	348	25	36	30.5	24.4	122	65	3.1	5.2	11.6	695	6.9	113	2.0	3.5	0.71	0.08
CEA 6194 05	18.6	270	28	27	79.5	33.4	294	92	4.0	5.7	13.6	598	7.9	111	3.0	2.5	0.33	0.11
HB 3032 06	15.8	317	24	24	353.6	23.9	902	655	5.5	9.4	13.8	591	5.9	51	2.0	2.8	0.49	bdl
HB 3032 20	14.4	267	27	23	4.7	15.1	116	56	2.9	3.6	12.4	599	7.6	56	2.4	2.5	0.61	bdl
RAM 5947 17	32.9	264	26	65	6.0	27.0	37	24	5.4	12.2	13.7	343	5.5	119	2.3	4.6	bdl	0.08
TR 6055 02	40.1	506	57	126	11.2	54.3	54	90	5.0	3.0	12.0	866	8.3	137	3.7	6.7	0.06	0.05

P-1 Tyre Type	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
AY 2844 01	0.7	0.01	0.11	270	7.30	14.58	1.87	7.70	1.62	0.44	1.53	0.22	1.25	0.26	0.70	0.09	0.63
AY 2844 02	1.0	0.01	0.13	278	6.97	13.44	1.75	7.02	1.43	0.39	1.32	0.21	1.16	0.23	0.62	0.08	0.61
AY 2844 03	16.5	2.87	0.04	338	6.85	13.15	1.68	6.96	1.41	0.38	1.42	0.19	1.14	0.25	0.65	0.09	0.66
AY 2844 04	0.5	bdl	0.09	276	6.84	13.63	1.78	7.31	1.53	0.41	1.43	0.21	1.15	0.24	0.64	0.09	0.61
AY 2844 06	0.8	bdl	bdl	278	6.89	13.15	1.81	7.44	1.57	0.40	1.41	0.21	1.21	0.26	0.66	0.09	0.65
AY 2989 04	1.6	0.20	0.10	339	7.69	14.70	1.77	7.18	1.48	0.38	1.24	0.21	1.17	0.25	0.67	0.10	0.64
AY 2989 06	18.3	2.93	0.14	269	7.85	14.23	1.77	7.04	1.41	0.36	1.32	0.21	1.16	0.25	0.66	0.10	0.62
AY 2989 07	1.2	bdl	0.15	255	7.63	14.88	1.80	7.37	1.49	0.39	1.32	0.21	1.22	0.26	0.72	0.11	0.65
AY 2989 10	1.6	bdl	0.09	329	7.53	13.90	1.74	6.91	1.45	0.34	1.21	0.20	1.17	0.24	0.68	0.09	0.60
AY 2989 11	0.6	bdl	0.15	307	9.26	17.99	2.20	8.99	1.82	0.49	1.63	0.25	1.56	0.32	0.86	0.11	0.76
AY 2989 12	14.7	3.78	0.12	267	8.29	15.93	1.95	7.96	1.65	0.43	1.42	0.23	1.31	0.28	0.74	0.10	0.70
AY 2989 13	7.3	bdl	0.11	269	8.83	15.90	1.96	7.82	1.60	0.41	1.37	0.23	1.31	0.28	0.76	0.11	0.71
AY 2989 14	1.2	bdl	0.08	318	7.93	15.53	1.82	7.18	1.42	0.35	1.28	0.19	1.19	0.25	0.69	0.10	0.61
AY 2989 15	7.2	0.10	0.10	304	9.06	17.84	2.23	9.12	1.96	0.49	1.66	0.25	1.50	0.31	0.77	0.10	0.70

P-1 Tyre Type	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
BSH 2885 01	9.6	1.36	0.18	227	6.38	11.34	1.53	6.13	1.30	0.31	1.01	0.16	0.97	0.20	0.52	0.07	0.51
BSH 2885 02	8.0	1.20	0.14	236	5.75	10.78	1.37	5.60	1.06	0.27	0.84	0.14	0.83	0.19	0.51	0.07	0.46
BSH 2885 04	10.5	1.06	0.12	224	6.13	10.58	1.40	5.65	1.13	0.28	0.58	0.15	0.93	0.21	0.51	0.07	0.50
CEA 6194 02	0.5	0.16	0.17	240	6.42	11.48	1.54	6.17	1.23	0.32	1.12	0.16	0.90	0.18	0.48	0.07	0.44
CEA 6194 02	1.6	0.30	0.17	255	7.15	12.75	1.70	6.78	1.40	0.36	1.19	0.18	1.05	0.21	0.55	0.08	0.53
CEA 6194 03	27.0	0.41	0.19	257	7.33	12.32	1.76	6.99	1.41	0.38	1.28	0.19	1.04	0.22	0.54	0.08	0.52
CEA 6194 04	3.4	0.43	0.15	272	7.38	12.99	1.69	6.76	1.37	0.37	1.28	0.19	1.12	0.24	0.61	0.09	0.61
CEA 6194 06	2.3	0.45	0.14	281	6.40	11.65	1.52	6.07	1.18	0.34	1.08	0.16	0.90	0.18	0.47	0.07	0.46
CEA 6194 07	0.7	0.12	0.15	297	7.05	11.88	1.65	6.57	1.26	0.38	1.17	0.19	1.02	0.22	0.53	0.08	0.54
CEA 6194 08	3.9	1.26	0.16	339	5.91	10.74	1.38	5.43	1.06	0.29	0.96	0.14	0.89	0.18	0.49	0.07	0.48
CEA 6194 09	15.9	0.24	0.20	216	8.17	13.92	1.93	7.71	1.48	0.44	1.41	0.22	1.27	0.27	0.65	0.09	0.64
CEA 6194 11	0.4	0.08	0.13	229	6.63	11.47	1.59	6.38	1.31	0.35	1.14	0.18	0.94	0.19	0.51	0.07	0.48
CEA 6194 12	0.9	0.12	0.20	336	7.60	12.93	1.78	7.18	1.46	0.39	1.26	0.19	1.13	0.24	0.59	0.08	0.59
CEA 6194 13	1.9	0.34	0.15	264	7.11	12.48	1.71	6.76	1.31	0.34	1.16	0.19	1.02	0.20	0.53	0.07	0.51
CEA 6194 14	0.9	0.16	0.15	395	7.22	12.60	1.67	6.67	1.37	0.38	1.26	0.21	1.16	0.25	0.63	0.09	0.61
CEA 6194 15	0.7	0.13	0.13	294	6.35	11.72	1.51	6.02	1.23	0.34	1.07	0.17	0.98	0.20	0.51	0.07	0.52
HB 3032 07	0.5	0.12	0.16	256	7.40	13.16	1.74	6.70	1.38	0.36	1.22	0.19	1.04	0.21	0.55	0.08	0.52
HB 3032 08	0.6	0.14	0.15	249	7.44	13.23	1.71	6.75	1.38	0.37	1.21	0.18	1.02	0.22	0.54	0.07	0.51
HB 3032 11	1.4	0.20	0.17	252	7.06	12.74	1.56	6.14	1.16	0.31	1.07	0.17	0.98	0.20	0.53	0.08	0.47
HB 3032 12	4.7	0.27	0.19	308	8.49	14.85	1.93	7.69	1.50	0.41	1.30	0.20	1.21	0.25	0.65	0.09	0.60
HB 3032 13	2.2	bdl	0.22	417	9.16	16.22	2.02	7.55	1.56	0.38	1.30	0.20	1.21	0.27	0.71	0.11	0.66
HB 3032 14	1.0	bdl	0.10	342	7.74	14.92	1.70	6.76	1.29	0.31	1.11	0.17	1.11	0.21	0.58	0.08	0.58
HB 3032 16	2.1	bdl	0.12	281	7.27	12.94	1.67	6.35	1.27	0.33	1.11	0.17	0.97	0.22	0.54	0.08	0.54
HB 3032 17	0.3	bdl	0.14	254	7.36	13.83	1.65	6.67	1.35	0.33	1.11	0.18	1.01	0.22	0.55	0.08	0.54
HB 3032 18	2.0	bdl	0.17	251	7.09	12.63	1.58	6.24	1.24	0.31	0.99	0.16	0.98	0.21	0.52	0.08	0.54
HB 3032 19	0.6	bdl	0.10	228	8.47	14.90	1.91	7.36	1.49	0.37	1.22	0.19	1.14	0.23	0.58	0.08	0.61

P-1 Tyre Type	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
HB 3032 21	0.4	bdl	0.13	269	7.37	13.85	1.63	6.30	1.25	0.30	1.07	0.16	1.00	0.22	0.56	0.08	0.51
HB 3032 22	2.1	0.41	0.10	330	7.72	14.98	1.77	6.90	1.35	0.35	1.11	0.19	1.06	0.22	0.61	0.08	0.59
HB 3032 23	0.5	bdl	0.13	242	7.66	14.52	1.77	6.87	1.31	0.34	1.16	0.19	1.02	0.22	0.58	0.08	0.53
JER 3835 06	0.6	bdl	0.12	234	7.74	12.96	1.70	6.79	1.40	0.37	1.14	0.19	1.08	0.23	0.61	0.09	0.58
JER 3835 09	33.8	16.29	0.10	276	8.13	14.46	1.86	7.30	1.41	0.38	1.23	0.19	1.19	0.24	0.65	0.09	0.60
JER 3835 11	0.7	bdl	0.12	247	7.74	14.43	1.77	7.14	1.39	0.35	1.23	0.20	1.11	0.23	0.62	0.08	0.54
JER 3835 15	3.8	bdl	0.16	323	8.81	14.76	1.93	7.64	1.50	0.41	1.36	0.23	1.37	0.30	0.80	0.10	0.68
NS 6362 06	0.6	0.16	0.20	330	7.85	13.09	1.86	7.45	1.40	0.42	1.34	0.20	1.11	0.22	0.61	0.08	0.56
RAM 3592 04	0.8	0.31	0.21	330	8.40	15.53	2.00	8.06	1.65	0.43	1.39	0.21	1.26	0.25	0.61	0.09	0.63
RAM 3592 05	0.8	0.31	0.21	333	8.56	15.44	1.98	8.21	1.62	0.43	1.50	0.22	1.30	0.26	0.67	0.09	0.62
RAM 3897 01	1.1	0.15	0.14	393	7.94	14.98	1.75	7.09	1.48	0.38	1.25	0.19	1.23	0.25	0.69	0.10	0.64
RAM 3897 02	0.8	0.17	0.14	385	8.10	15.46	1.85	7.27	1.48	0.40	1.35	0.20	1.22	0.27	0.71	0.09	0.66
RAM 3897 03	0.3	0.11	0.15	252	6.62	11.70	1.49	6.10	1.24	0.33	1.03	0.17	0.94	0.21	0.55	0.07	0.51
RAM 3897 06	0.4	0.10	0.18	298	7.81	13.18	1.78	7.27	1.47	0.39	1.31	0.22	1.25	0.27	0.71	0.10	0.64
RAM 3897 07	0.3	0.11	0.16	262	6.63	11.84	1.50	6.12	1.21	0.31	1.06	0.17	0.99	0.22	0.56	0.07	0.53
RAM 3897 08	1.2	0.22	0.14	234	7.32	14.15	1.75	7.07	1.49	0.37	1.19	0.19	1.15	0.24	0.62	0.08	0.60
RAM 4740 04	10.3	0.36	0.14	288	6.17	9.75	1.40	6.06	1.31	0.31	0.99	0.17	0.90	0.20	0.50	0.06	0.47
RAM 4740 06	13.2	0.48	0.15	271	7.57	13.38	1.71	7.16	1.44	0.33	1.22	0.20	1.24	0.28	0.68	0.09	0.68
RAM 4740 08	14.5	0.43	0.17	283	7.71	12.95	1.80	7.19	1.48	0.36	1.31	0.21	1.21	0.27	0.71	0.10	0.65
RAM 4740 10	13.1	0.35	0.15	285	7.56	13.10	1.76	7.22	1.49	0.33	1.22	0.20	1.25	0.27	0.65	0.09	0.61
RAM 4768 04	13.6	1.82	0.16	346	6.54	10.89	1.49	6.16	1.24	0.31	1.00	0.19	1.03	0.22	0.60	0.08	0.54
RAM 4768 06	11.7	1.34	0.13	219	6.70	11.67	1.62	6.50	1.31	0.32	1.07	0.18	1.05	0.21	0.58	0.07	0.51
RAM 4768 11	10.8	1.10	0.12	198	6.27	11.61	1.49	6.25	1.19	0.28	1.01	0.16	1.05	0.20	0.54	0.08	0.48
RAM 5947 26	14.7	0.38	0.18	327	8.99	15.53	2.03	8.57	1.76	0.45	1.38	0.25	1.42	0.32	0.83	0.11	0.86
RAM 5947 27	9.5	0.19	0.16	252	6.77	12.11	1.61	6.50	1.27	0.38	1.13	0.18	1.07	0.21	0.62	0.08	0.50
RAM 5947 28	10.8	0.23	0.16	263	7.50	13.58	1.84	7.68	1.46	0.42	1.48	0.20	1.16	0.24	0.63	0.09	0.61
RAM 5947 30	13.0	0.15	0.14	251	6.41	11.16	1.47	5.90	1.25	0.34	1.03	0.17	0.96	0.21	0.57	0.08	0.53

P-1 Tyre Type	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
RAM 6297 01	0.9	bdl	0.12	209	6.49	11.64	1.54	6.20	1.24	0.33	1.22	0.17	1.00	0.21	0.53	0.08	0.52
RAM 6297 02	10.3	0.48	0.12	241	6.56	11.95	1.55	6.23	1.20	0.33	1.24	0.18	1.02	0.22	0.58	0.08	0.56
RAM 6297 03	5.5	bdl	0.14	259	7.47	13.78	1.83	7.47	1.52	0.41	1.43	0.22	1.23	0.25	0.65	0.09	0.63
RAM 6297 08	1.0	bdl	0.13	232	8.24	16.29	2.06	8.57	1.72	0.45	1.65	0.24	1.39	0.29	0.75	0.10	0.71
RAM 6297 09	1.8	bdl	0.06	240	8.18	15.06	1.93	7.50	1.61	0.41	1.42	0.22	1.24	0.26	0.69	0.10	0.69
RAM 6297 10	1.1	bdl	bdl	305	7.06	13.57	1.69	6.76	1.32	0.35	1.22	0.19	1.05	0.24	0.63	0.09	0.63
RAM 6297 11	0.9	bdl	bdl	334	7.40	14.43	1.78	7.06	1.40	0.37	1.31	0.19	1.07	0.23	0.66	0.09	0.65
RAM 6297 12	0.6	bdl	0.08	262	7.29	12.86	1.74	7.26	1.49	0.37	1.35	0.21	1.15	0.24	0.63	0.08	0.59
RAM 6297 13	0.8	bdl	bdl	364	7.49	14.58	1.82	7.19	1.47	0.37	1.38	0.20	1.15	0.23	0.63	0.09	0.65
RAM 6297 14	1.7	bdl	bdl	226	7.58	14.14	1.80	7.18	1.41	0.36	1.34	0.20	1.17	0.26	0.67	0.09	0.66
RAM 6297 15	4.9	bdl	bdl	234	7.49	13.96	1.78	6.78	1.40	0.37	1.28	0.20	1.15	0.25	0.65	0.10	0.69
RAM 6297 16	7.2	bdl	bdl	358	7.54	14.84	1.82	7.14	1.40	0.38	1.29	0.21	1.21	0.25	0.63	0.09	0.63
RAM 6490 05	1.5	bdl	0.08	299	8.17	13.96	1.92	7.79	1.61	0.43	1.38	0.22	1.23	0.26	0.65	0.09	0.59
RAM 6490 06	15.7	0.37	bdl	333	7.98	13.17	1.86	7.45	1.52	0.40	1.30	0.22	1.20	0.26	0.64	0.09	0.61
SEP 3791 13	27.9	1.35	0.09	276	7.95	13.28	1.82	7.47	1.48	0.29	1.32	0.22	1.33	0.26	0.81	0.10	0.68
SEP 3791 15	11.8	0.54	bdl	272	6.95	11.68	1.66	6.87	1.32	0.20	1.20	0.19	1.09	0.23	0.61	0.08	0.56
TIB 5583 08	0.9	0.13	0.23	258	7.03	12.37	1.61	6.30	1.27	0.34	1.15	0.17	1.03	0.23	0.53	0.08	0.56
TIB 5583 09	2.9	0.59	0.19	411	7.79	15.16	1.78	7.05	1.42	0.39	1.28	0.21	1.17	0.26	0.65	0.09	0.67
TIB 5583 11	1.8	0.28	0.18	328	7.36	13.50	1.68	6.85	1.38	0.35	1.13	0.18	1.12	0.23	0.64	0.09	0.57
TIB 5583 12	0.5	0.16	0.20	249	6.86	13.03	1.63	6.63	1.32	0.35	1.16	0.19	1.05	0.21	0.58	0.07	0.52
TIB 5583 13	1.2	0.16	0.15	311	7.09	13.63	1.65	6.59	1.28	0.34	1.11	0.19	1.07	0.23	0.60	0.09	0.57
TIB 5583 15	1.4	0.30	0.11	329	8.45	16.89	2.09	8.76	1.80	0.43	1.52	0.23	1.34	0.28	0.75	0.10	0.64
TIB 5583 16	1.3	bdl	0.15	244	7.19	13.33	1.69	6.84	1.33	0.36	1.25	0.18	1.12	0.23	0.62	0.09	0.64
TIB 5583 17	0.6	bdl	0.14	263	8.63	16.04	2.08	8.62	1.73	0.44	1.52	0.24	1.28	0.26	0.66	0.10	0.65
TIB 5583 18	0.4	bdl	0.18	202	6.79	11.77	1.56	6.36	1.24	0.34	1.09	0.16	1.01	0.20	0.53	0.08	0.48
TIB 5583 19	0.6	bdl	0.17	277	7.47	13.55	1.70	6.97	1.40	0.36	1.24	0.19	1.13	0.24	0.66	0.09	0.59
TIB 5583 22	0.5	bdl	0.17	240	7.07	13.25	1.64	6.74	1.31	0.34	1.12	0.18	1.07	0.21	0.59	0.08	0.57

P-1 Tyre Type	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
TIB 5583 23	0.4	bdl	0.18	276	7.80	13.84	1.78	7.76	1.52	0.40	1.38	0.21	1.20	0.26	0.70	0.09	0.62
TIB 5583 24	2.6	bdl	0.15	323	7.81	13.75	1.83	7.52	1.61	0.41	1.36	0.21	1.25	0.25	0.65	0.09	0.62
TIB 5583 25	0.4	bdl	0.14	228	7.14	12.49	1.66	6.83	1.39	0.35	1.13	0.17	1.05	0.23	0.56	0.08	0.54
TIB 5583 26	0.4	bdl	0.15	335	6.60	11.45	1.51	5.98	1.27	0.32	1.10	0.16	1.01	0.23	0.58	0.08	0.55
TIB 5583 27	0.8	bdl	0.11	209	7.05	12.89	1.61	6.49	1.31	0.33	1.09	0.19	1.01	0.22	0.53	0.08	0.58
TIB 5583 28	1.1	bdl	0.12	327	7.88	13.67	1.81	7.33	1.47	0.38	1.26	0.21	1.20	0.25	0.63	0.10	0.62
TIB 5583 29	0.5	bdl	0.11	216	7.55	14.29	1.78	7.18	1.44	0.37	1.23	0.20	1.15	0.26	0.62	0.09	0.62
TIB 5583 30	0.9	bdl	0.16	293	7.97	14.27	1.92	7.94	1.57	0.42	1.42	0.20	1.18	0.25	0.65	0.09	0.59
P-2 Syro-Palestine Type	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
BSH 2885 03	13.1	1.40	0.10	84	6.46	11.62	1.41	5.40	1.04	0.19	0.61	0.13	0.77	0.16	0.42	0.05	0.38
HB 3032 04	2.7	0.24	0.12	87	6.55	11.39	1.33	4.83	0.92	0.19	0.77	0.11	0.68	0.14	0.38	0.05	0.36
RAM 4740 05	19.2	0.71	0.15	148	8.89	16.96	1.89	7.55	1.36	0.26	1.08	0.16	0.95	0.19	0.53	0.07	0.57
SEP 3791 16	32.1	1.63	bdl	127	7.02	12.67	1.50	5.93	1.23	0.05	0.71	0.13	0.88	0.15	0.45	0.06	0.44
TIB 5583 14	3.0	0.23	0.17	89	6.09	11.05	1.29	4.91	0.97	0.20	0.66	0.12	0.64	0.12	0.31	0.04	0.34
TIB 5583 20	0.8	bdl	0.09	85	6.31	11.02	1.31	4.98	1.01	0.20	0.78	0.13	0.70	0.14	0.38	0.05	0.35
BSH 2885 05	20.8	0.81	0.20	539	5.50	10.12	1.15	4.20	0.82	0.13	0.53	0.12	0.67	0.16	0.47	0.07	0.51
BSH 2885 07	22.9	0.84	0.19	361	4.95	13.80	1.08	3.96	0.81	0.15	0.50	0.15	0.80	0.16	0.44	0.06	0.52
BSH 2885 08	14.6	0.84	0.17	248	8.22	15.83	1.68	6.19	1.08	0.19	0.63	0.15	0.86	0.18	0.50	0.07	0.55
BSH 2885 11	10.5	0.52	0.13	263	8.08	15.84	1.75	6.21	1.14	0.11	0.68	0.15	0.85	0.18	0.51	0.07	0.53
BSH 2885 12	16.6	1.32	0.21	473	5.42	11.03	1.15	4.28	0.86	0.11	0.42	0.12	0.76	0.16	0.45	0.07	0.53
P-3 Nishapur Colourless	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
CEA 6194 10	7.4	0.28	0.21	136	4.09	8.19	0.91	3.42	0.66	0.15	0.62	0.09	0.58	0.12	0.34	0.05	0.34
HB 3032 09	0.4	0.07	0.12	83	2.59	5.31	0.54	2.01	0.39	0.08	0.34	0.06	0.30	0.07	0.20	0.03	0.23
HB 3032 15	0.5	bdl	0.17	110	4.37	8.70	0.92	3.54	0.70	0.11	0.54	0.09	0.57	0.12	0.32	0.05	0.37
JER 5124 31	0.4	bdl	0.14	136	4.14	7.92	0.85	2.96	0.58	0.13	0.47	0.09	0.56	0.12	0.31	0.05	0.35

P-3 Nishapur Colourless	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
RAM 3592 06	0.4	0.11	0.17	173	3.18	6.10	0.70	2.75	0.55	0.11	0.51	0.09	0.50	0.11	0.28	0.05	0.30
RAM 3897 04	0.4	0.08	0.15	77	5.68	11.80	1.25	4.74	0.83	0.18	0.74	0.12	0.67	0.14	0.40	0.06	0.45
RAM 4740 02	13.3	0.47	0.18	127	3.41	6.48	0.76	2.82	0.65	0.11	0.54	0.07	0.52	0.10	0.31	0.04	0.35
RAM 4740 12	10.2	0.24	0.17	95	3.87	7.67	0.88	3.49	0.82	0.08	0.58	0.10	0.63	0.13	0.36	0.05	0.33
RAM 4740 13	11.6	0.20	0.12	115	3.69	7.23	0.84	3.28	0.64	0.09	0.45	0.09	0.60	0.11	0.32	0.06	0.36
RAM 4768 05	12.5	1.53	0.13	114	3.13	6.22	0.74	2.74	0.58	0.08	0.39	0.09	0.49	0.10	0.27	0.05	0.29
RAM 4768 10	9.9	0.97	0.13	106	3.57	7.38	0.79	3.02	0.58	0.06	0.43	0.08	0.50	0.12	0.30	0.05	0.29
RAM 5947 29	11.1	0.16	0.17	109	3.41	6.89	0.80	2.91	0.62	0.10	0.44	0.10	0.60	0.12	0.28	0.05	0.37
RAM 5947 31	11.6	0.23	0.18	122	3.47	6.74	0.77	3.04	0.62	0.13	0.44	0.08	0.47	0.11	0.31	0.04	0.30
RAM 6297 07	0.4	bdl	bdl	91	2.97	6.38	0.67	2.60	0.56	0.11	0.49	0.07	0.42	0.09	0.24	0.03	0.30
RAM 6490 11	0.6	bdl	0.11	165	7.66	14.76	1.58	5.90	1.06	0.24	0.84	0.15	0.83	0.17	0.51	0.07	0.46
RAM 6490 12	0.5	bdl	0.15	102	3.52	7.07	0.76	2.83	0.56	0.12	0.50	0.09	0.47	0.11	0.30	0.03	0.33
SEP 3791 14	14.8	0.51	0.05	214	6.97	13.05	1.52	5.81	1.22	0.13	0.83	0.15	0.94	0.20	0.52	0.07	0.62
TIB 5583 21	0.3	bdl	0.15	106	3.43	6.72	0.76	2.87	0.57	0.11	0.48	0.08	0.50	0.11	0.29	0.04	0.30
P-4 Nishapur Coloured	**SnO_2**	**Sb_2O_3**	**Cs_2O**	**BaO**	**La_2O_3**	**CeO_2**	**PrO_2**	**Nd_2O_3**	**Sm_2O_3**	**Eu_2O_3**	**Gd_2O_3**	**Tb_2O_3**	**Dy_2O_3**	**Ho_2O_3**	**Er_2O_3**	**Tm_2O_3**	**Yb_2O_3**
CEA W2S3 04	108.8	3.36	0.24	346	6.32	12.40	1.49	5.88	1.14	0.28	0.99	0.16	0.95	0.19	0.55	0.09	0.60
JER 3835 07	7.0	1.07	0.25	386	11.33	23.04	2.44	8.97	1.73	0.35	1.42	0.25	1.43	0.29	0.82	0.12	0.80
RAM 3897 05	20.0	7.77	0.23	244	9.28	18.11	1.91	7.39	1.39	0.29	1.08	0.17	1.02	0.20	0.58	0.09	0.61
RAM 4768 08	33.6	6.06	0.30	206	10.85	21.99	2.38	9.29	1.60	0.30	1.32	0.21	1.34	0.25	0.78	0.11	0.77
RAM 4768 09	34.0	7.27	0.12	214	8.16	15.08	1.86	7.30	1.53	0.31	1.16	0.22	1.24	0.27	0.73	0.10	0.71
RAM 6297 05	8.7	3.41	0.45	311	12.83	26.61	2.91	11.03	2.08	0.42	1.78	0.25	1.43	0.30	0.83	0.12	1.00
RAM 6490 07	29.6	3.39	0.16	233	8.21	12.92	1.74	6.78	1.36	0.32	1.21	0.17	1.01	0.21	0.55	0.07	0.53
RAM 6490 08	14.9	1.82	0.30	202	9.54	19.65	2.08	7.73	1.45	0.28	1.17	0.18	1.07	0.23	0.64	0.09	0.70
RAM 6490 09	12.1	8.92	0.43	302	12.33	25.05	2.58	9.47	1.74	0.35	1.39	0.23	1.25	0.28	0.73	0.11	0.75
TIB 5583 07	10.2	0.87	0.44	369	9.98	20.53	2.18	8.13	1.53	0.28	1.18	0.19	1.12	0.23	0.59	0.08	0.67

Outliers	SnO_2	Sb_2O_3	Cs_2O	BaO	La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3
AY 2989 08	1.3	bdl	0.35	225	6.73	12.45	1.48	5.60	1.05	0.27	0.83	0.16	0.89	0.17	0.52	0.07	0.52
BSH 2885 09	15.6	0.70	0.09	54	7.04	13.99	1.50	5.47	1.00	0.14	0.54	0.12	0.77	0.17	0.44	0.06	0.48
BSH 2885 10	11.4	0.43	0.06	194	7.27	14.41	1.51	5.28	1.11	0.10	0.38	0.11	0.72	0.16	0.43	0.06	0.50
CEA 6194 01	13.0	2.52	0.19	220	8.57	17.08	1.89	7.03	1.36	0.29	1.17	0.18	1.00	0.20	0.55	0.08	0.59
CEA 6194 05	26.6	14.21	0.15	257	7.83	14.91	1.85	7.23	1.41	0.37	1.37	0.20	1.16	0.25	0.63	0.09	0.70
HB 3032 06	20.8	3.85	0.19	166	7.06	13.00	1.48	5.65	1.04	0.26	0.88	0.13	0.77	0.16	0.42	0.06	0.41
HB 3032 20	45.7	0.11	0.12	223	8.09	14.95	1.75	6.65	1.47	0.31	1.10	0.17	1.02	0.21	0.58	0.08	0.53
RAM 5947 17	13.3	1.13	0.21	329	7.56	15.39	1.71	6.39	1.20	0.30	0.80	0.15	0.93	0.21	0.55	0.08	0.62
TR 6055 02	1.1	0.35	0.19	287	10.66	20.73	2.23	7.99	1.58	0.36	1.25	0.20	1.19	0.25	0.72	0.10	0.71

P-1 Tyre Type	Lu_2O_3	HfO_2	Ta_2O_3	WO	Pt	Au	PbO	Bi	ThO_2	UO_2
AY 2844 01	0.09	1.05	0.10	0.37	bdl	bdl	5.9	bdl	0.95	0.48
AY 2844 02	0.08	1.11	0.12	0.39	bdl	bdl	14.9	bdl	1.01	0.51
AY 2844 03	0.10	1.22	0.12	0.27	bdl	bdl	142.0	bdl	0.98	0.56
AY 2844 04	0.08	1.07	0.11	0.49	bdl	bdl	6.4	bdl	0.93	0.46
AY 2844 06	0.09	1.13	0.12	0.47	bdl	bdl	6.9	bdl	0.96	0.63
AY 2989 04	0.10	1.20	0.13	0.30	bdl	bdl	19.5	bdl	1.02	0.54
AY 2989 06	0.10	1.27	0.12	0.30	bdl	bdl	238.3	bdl	1.10	0.59
AY 2989 07	0.09	1.10	0.10	0.24	bdl	bdl	7.7	bdl	0.90	0.45
AY 2989 10	0.09	1.20	0.12	0.31	bdl	bdl	16.5	bdl	1.00	0.47
AY 2989 11	0.11	1.29	0.14	0.59	bdl	bdl	7.1	bdl	1.18	0.68
AY 2989 12	0.10	1.30	0.14	0.43	bdl	bdl	363.4	bdl	1.14	0.64
AY 2989 13	0.11	1.33	0.15	0.18	bdl	bdl	97.4	bdl	1.24	0.67
AY 2989 14	0.10	1.22	0.13	0.24	bdl	bdl	15.6	bdl	1.10	1.04
AY 2989 15	0.09	1.26	0.12	0.42	bdl	bdl	10.1	bdl	1.10	0.58
BSH 2885 01	0.08	1.00	0.11	0.34	bdl	bdl	7.0	bdl	0.89	0.46
BSH 2885 02	0.07	0.82	0.08	0.31	bdl	bdl	6.1	bdl	0.72	0.42
BSH 2885 04	0.08	1.00	0.08	0.22	bdl	bdl	6.9	bdl	0.84	0.41
CEA 6194 02	0.06	0.83	0.08	0.28	bdl	bdl	3.3	bdl	0.78	0.45
CEA 6194 02	0.08	0.97	0.09	0.36	bdl	bdl	12.3	bdl	0.93	0.54
CEA 6194 03	0.07	0.86	0.08	0.12	bdl	bdl	28.9	bdl	0.86	0.36
CEA 6194 04	0.08	0.97	0.09	0.29	bdl	bdl	17.7	bdl	0.91	0.53
CEA 6194 06	0.07	0.89	0.09	0.36	bdl	bdl	13.1	bdl	0.82	0.43
CEA 6194 07	0.08	0.87	0.08	0.19	bdl	bdl	7.3	bdl	0.81	0.51
CEA 6194 08	0.07	0.90	0.08	0.23	bdl	bdl	20.8	bdl	0.75	0.44
CEA 6194 09	0.09	0.87	0.09	0.10	bdl	bdl	29.6	bdl	0.90	0.37
CEA 6194 11	0.07	0.81	0.08	0.22	bdl	bdl	3.0	bdl	0.79	0.37
CEA 6194 12	0.08	0.91	0.09	0.13	bdl	bdl	12.0	bdl	0.90	0.50
CEA 6194 13	0.07	0.93	0.10	0.33	bdl	bdl	18.3	bdl	0.94	0.50
CEA 6194 14	0.08	0.81	0.08	0.24	bdl	bdl	5.1	bdl	0.79	0.38
CEA 6194 15	0.07	0.84	0.08	0.35	bdl	bdl	5.3	bdl	0.76	0.46
HB 3032 07	0.07	0.90	0.09	0.25	bdl	bdl	2.9	bdl	0.85	0.38
HB 3032 08	0.07	0.89	0.08	0.27	bdl	bdl	3.3	bdl	0.89	0.40
HB 3032 11	0.07	0.92	0.09	0.13	bdl	bdl	6.8	bdl	0.86	0.35
HB 3032 12	0.09	0.85	0.09	0.34	bdl	bdl	9.3	bdl	0.90	0.47
HB 3032 13	0.10	1.15	0.12	0.39	bdl	bdl	10.8	bdl	1.19	0.73
HB 3032 14	0.08	1.09	0.12	0.14	bdl	bdl	8.8	bdl	1.01	0.49
HB 3032 16	0.08	1.03	0.11	0.16	bdl	bdl	8.5	bdl	0.97	0.45
HB 3032 17	0.08	0.93	0.08	0.32	bdl	bdl	3.2	bdl	0.87	0.50
HB 3032 18	0.07	0.97	0.09	0.13	bdl	bdl	9.2	bdl	0.87	0.36
HB 3032 19	0.09	1.12	0.13	0.22	bdl	bdl	4.3	bdl	1.20	0.44
HB 3032 21	0.08	0.88	0.09	0.25	bdl	bdl	3.0	bdl	0.90	0.42
HB 3032 22	0.08	1.11	0.11	0.24	bdl	bdl	116.9	bdl	1.03	0.54
HB 3032 23	0.08	1.05	0.10	0.28	bdl	bdl	3.7	bdl	0.90	0.38

P-1 Tyre Type	Lu_2O_3	HfO_2	Ta_2O_3	WO	Pt	Au	PbO	Bi	ThO_2	UO_2
JER 3835 06	0.08	1.02	0.11	0.20	bdl	bdl	5.5	bdl	0.95	0.51
JER 3835 09	0.09	1.29	0.13	0.23	bdl	bdl	486.9	0.07	1.11	0.65
JER 3835 11	0.09	1.14	0.12	0.38	bdl	bdl	6.0	bdl	0.99	0.44
JER 3835 15	0.10	0.94	0.10	0.15	bdl	bdl	12.8	bdl	0.97	0.59
NS 6362 06	0.07	0.81	0.08	0.21	bdl	bdl	6.8	bdl	0.80	0.47
RAM 3592 04	0.09	1.14	0.12	0.57	bdl	bdl	8.9	bdl	1.07	0.66
RAM 3592 05	0.09	1.10	0.12	0.58	bdl	bdl	8.4	bdl	1.07	0.67
RAM 3897 01	0.09	1.21	0.12	0.18	bdl	bdl	8.9	bdl	1.10	0.52
RAM 3897 02	0.10	1.00	0.10	0.18	bdl	bdl	9.1	bdl	0.99	0.57
RAM 3897 03	0.08	0.94	0.07	0.17	bdl	bdl	3.1	bdl	0.77	0.35
RAM 3897 06	0.09	0.92	0.08	0.14	bdl	bdl	6.8	bdl	0.85	0.51
RAM 3897 07	0.08	0.95	0.08	0.21	bdl	bdl	3.0	bdl	0.77	0.40
RAM 3897 08	0.09	1.05	0.10	0.17	bdl	bdl	9.6	bdl	0.90	0.52
RAM 4740 04	0.05	0.79	0.06	0.13	bdl	bdl	12.2	0.09	0.67	0.54
RAM 4740 06	0.09	1.12	0.11	0.18	bdl	bdl	10.6	bdl	1.01	0.48
RAM 4740 08	0.09	1.09	0.11	0.30	bdl	bdl	17.5	bdl	1.04	0.54
RAM 4740 10	0.09	1.06	0.10	0.32	bdl	bdl	17.5	bdl	1.00	0.56
RAM 4768 04	0.07	0.80	0.07	0.08	bdl	bdl	10.3	bdl	0.78	0.57
RAM 4768 06	0.07	1.00	0.09	0.42	bdl	bdl	6.5	bdl	0.90	0.44
RAM 4768 11	0.07	0.95	0.09	0.45	bdl	bdl	4.2	bdl	0.82	0.36
RAM 5947 26	0.12	1.30	0.13	0.70	bdl	bdl	17.6	bdl	1.27	0.85
RAM 5947 27	0.07	0.95	0.09	0.28	bdl	bdl	7.4	bdl	0.86	0.52
RAM 5947 28	0.09	0.94	0.08	0.41	bdl	bdl	6.1	bdl	0.92	0.48
RAM 5947 30	0.07	1.02	0.09	0.25	bdl	bdl	4.9	bdl	0.87	0.46
RAM 6297 01	0.07	1.01	0.10	0.24	bdl	bdl	4.0	bdl	0.87	0.44
RAM 6297 02	0.08	1.14	0.10	0.28	bdl	bdl	82.1	bdl	0.93	0.50
RAM 6297 03	0.09	1.18	0.12	0.38	bdl	bdl	90.9	bdl	1.06	0.57
RAM 6297 08	0.10	1.26	0.13	0.39	bdl	bdl	6.4	bdl	1.14	0.45
RAM 6297 09	0.10	1.28	0.15	0.14	bdl	bdl	62.7	bdl	1.23	0.63
RAM 6297 10	0.08	1.14	0.11	0.14	bdl	bdl	8.7	bdl	1.00	0.49
RAM 6297 11	0.09	1.24	0.15	0.22	bdl	bdl	12.1	bdl	1.09	0.49
RAM 6297 12	0.08	0.99	0.10	0.39	bdl	bdl	6.9	bdl	0.93	0.56
RAM 6297 13	0.08	1.32	0.15	0.23	bdl	bdl	10.6	bdl	1.14	0.52
RAM 6297 14	0.10	1.29	0.13	0.12	bdl	bdl	38.5	bdl	1.11	0.58
RAM 6297 15	0.10	1.25	0.13	0.12	bdl	bdl	60.2	bdl	1.08	0.57
RAM 6297 16	0.09	1.16	0.13	0.21	bdl	bdl	136.1	bdl	1.08	0.55
RAM 6490 05	0.09	0.97	0.10	0.38	bdl	bdl	7.1	bdl	0.94	0.49
RAM 6490 06	0.09	1.01	0.09	0.15	bdl	bdl	59.0	bdl	0.96	0.60
SEP 3791 13	0.12	1.28	0.13	0.22	bdl	bdl	123.2	bdl	1.14	0.74
SEP 3791 15	0.09	0.95	0.09	0.21	bdl	bdl	7.4	bdl	0.89	0.49
TIB 5583 08	0.09	1.01	0.09	0.12	bdl	bdl	5.0	bdl	0.88	0.36
TIB 5583 09	0.09	1.15	0.10	0.20	bdl	bdl	39.2	bdl	1.01	0.56
TIB 5583 11	0.09	1.19	0.11	0.05	bdl	bdl	16.5	bdl	1.04	0.64
TIB 5583 12	0.07	0.94	0.08	0.29	bdl	bdl	5.6	bdl	0.79	0.38
TIB 5583 13	0.09	1.18	0.11	0.18	bdl	bdl	9.2	bdl	0.99	0.51

P-1 Tyre Type	Lu_2O_3	HfO_2	Ta_2O_3	WO	Pt	Au	PbO	Bi	ThO_2	UO_2
TIB 5583 15	0.10	1.22	0.11	0.40	bdl	bdl	11.7	bdl	1.06	0.71
TIB 5583 16	0.09	1.07	0.10	0.09	bdl	bdl	13.4	bdl	0.95	0.46
TIB 5583 17	0.09	1.20	0.13	0.30	bdl	bdl	7.6	bdl	1.11	0.53
TIB 5583 18	0.07	1.01	0.10	0.25	bdl	bdl	3.1	bdl	0.91	0.43
TIB 5583 19	0.09	1.05	0.09	0.27	bdl	bdl	5.1	bdl	0.93	0.52
TIB 5583 22	0.08	1.03	0.10	0.32	bdl	bdl	4.3	bdl	0.91	0.44
TIB 5583 23	0.09	1.03	0.09	0.39	bdl	bdl	7.4	bdl	0.97	0.59
TIB 5583 24	0.09	0.94	0.09	0.34	bdl	bdl	10.6	bdl	0.89	0.49
TIB 5583 25	0.08	1.00	0.11	0.28	bdl	bdl	3.5	bdl	0.90	0.45
TIB 5583 26	0.08	0.97	0.08	0.15	bdl	bdl	3.7	bdl	0.85	0.47
TIB 5583 27	0.08	1.09	0.10	0.24	bdl	bdl	6.0	bdl	0.96	0.52
TIB 5583 28	0.09	1.24	0.12	0.12	bdl	bdl	7.8	bdl	1.10	0.63
TIB 5583 29	0.09	1.43	0.12	0.13	bdl	bdl	5.0	bdl	1.00	0.49
TIB 5583 30	0.09	1.05	0.10	0.38	bdl	bdl	7.3	bdl	0.99	0.54
P-2 Syro-Palestine Type	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
BSH 2885 03	0.06	1.21	0.09	0.08	bdl	bdl	19.8	bdl	1.10	0.50
HB 3032 04	0.05	1.00	0.06	0.06	bdl	bdl	17.0	bdl	1.00	0.68
RAM 4740 05	0.09	3.20	0.11	1.73	bdl	bdl	21.9	bdl	2.28	0.97
SEP 3791 16	0.07	2.14	0.11	0.09	bdl	bdl	104.6	0.06	1.29	0.71
TIB 5583 14	0.05	0.98	0.07	0.05	bdl	bdl	11.2	bdl	0.98	0.48
TIB 5583 20	0.05	1.28	0.07	0.04	bdl	bdl	8.6	bdl	1.00	0.62
BSH 2885 05	0.08	3.37	0.16	0.13	bdl	bdl	20.0	bdl	1.52	1.41
BSH 2885 07	0.07	2.78	0.12	0.09	bdl	bdl	24.8	bdl	1.30	1.16
BSH 2885 08	0.10	3.60	0.17	0.35	bdl	bdl	8.1	bdl	1.83	0.91
BSH 2885 11	0.09	3.48	0.15	0.14	bdl	bdl	6.0	bdl	1.83	0.97
BSH 2885 12	0.09	4.24	0.16	0.51	bdl	bdl	28.6	bdl	1.56	1.26
P-3 Nishapur Colourless	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
CEA 6194 10	0.05	1.06	0.08	0.36	bdl	bdl	100.2	bdl	1.07	0.54
HB 3032 09	0.03	0.78	0.05	0.11	bdl	bdl	1.4	bdl	0.82	0.43
HB 3032 15	0.05	1.30	0.08	0.10	bdl	bdl	1.8	bdl	1.14	0.55
JER 5124 31	0.06	1.24	0.08	0.20	bdl	bdl	1.7	bdl	1.14	0.62
RAM 3592 06	0.05	0.79	0.08	0.24	bdl	bdl	2.1	bdl	0.98	0.56
RAM 3897 04	0.07	1.87	0.08	0.13	bdl	bdl	3.1	bdl	1.20	0.46
RAM 4740 02	0.04	0.95	0.07	0.19	bdl	bdl	4.2	bdl	0.96	0.49
RAM 4740 12	0.05	1.26	0.07	0.06	bdl	bdl	4.8	bdl	1.10	0.52
RAM 4740 13	0.05	1.15	0.08	0.21	bdl	bdl	5.8	bdl	1.02	0.53
RAM 4768 05	0.04	0.94	0.06	0.77	bdl	bdl	3.3	bdl	0.89	0.47
RAM 4768 10	0.04	1.32	0.06	0.09	bdl	bdl	3.9	bdl	0.94	0.46
RAM 5947 29	0.05	0.95	0.07	0.52	bdl	bdl	4.7	bdl	1.03	0.55
RAM 5947 31	0.04	0.88	0.07	0.45	bdl	bdl	4.3	bdl	0.97	0.55
RAM 6297 07	0.04	0.75	0.04	0.08	bdl	bdl	1.9	bdl	0.71	0.38
RAM 6490 11	0.08	3.36	0.12	0.38	bdl	bdl	2.9	bdl	1.81	0.62
RAM 6490 12	0.04	0.94	0.07	0.39	bdl	bdl	1.5	bdl	0.91	0.50
SEP 3791 14	0.09	2.83	0.12	0.38	bdl	bdl	10.4	bdl	1.81	0.57

TIB 5583 21	0.05	1.12	0.08	0.27	bdl	bdl	1.6	bdl	0.93	0.53
P-4 Nishapur Coloured	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
CEA W2S3 04	0.09	2.14	0.15	1.27	bdl	bdl	649.3	0.07	1.58	0.66
JER 3835 07	0.13	3.66	0.21	0.22	bdl	bdl	122.2	bdl	3.24	1.12
RAM 3897 05	0.10	2.66	0.16	0.26	bdl	bdl	168.3	0.10	2.25	0.91
RAM 4768 08	0.11	3.20	0.19	0.21	bdl	bdl	144.3	0.18	2.73	1.32
RAM 4768 09	0.11	3.05	0.17	0.21	bdl	bdl	228.0	0.10	1.80	0.83
RAM 6297 05	0.15	5.92	0.26	0.57	bdl	bdl	295.8	0.22	4.00	1.23
RAM 6490 07	0.08	0.71	0.12	0.14	bdl	0.07	79.2	0.05	1.34	1.06
RAM 6490 08	0.10	3.07	0.20	0.19	bdl	bdl	195.5	0.17	2.60	1.04
RAM 6490 09	0.12	3.33	0.21	0.29	bdl	bdl	310.4	0.44	2.79	1.45
TIB 5583 07	0.10	3.00	0.16	0.19	bdl	bdl	73.5	bdl	2.31	1.10
Outliers	**Lu_2O_3**	**HfO_2**	**Ta_2O_3**	**WO**	**Pt**	**Au**	**PbO**	**Bi**	**ThO_2**	**UO_2**
AY 2989 08	0.08	1.82	0.13	0.16	bdl	bdl	11.2	bdl	1.58	0.69
BSH 2885 09	0.08	3.53	0.14	0.09	bdl	bdl	2.1	bdl	1.66	0.45
BSH 2885 10	0.07	4.05	0.13	0.11	bdl	bdl	12.3	bdl	1.73	0.66
CEA 6194 01	0.08	2.35	0.11	0.21	bdl	bdl	604.1	0.07	1.88	0.66
CEA 6194 05	0.09	2.24	0.16	0.21	bdl	bdl	283.1	0.08	1.28	0.72
HB 3032 06	0.07	1.08	0.09	0.17	bdl	bdl	538.7	0.13	1.12	0.65
HB 3032 20	0.08	1.16	0.11	0.20	bdl	0.07	414.4	bdl	1.14	0.79
RAM 5947 17	0.10	2.81	0.15	0.31	bdl	bdl	8.1	bdl	1.92	0.74
TR 6055 02	0.11	2.62	0.18	0.24	bdl	bdl	5.5	bdl	2.48	1.26

Appendix K: Analytical Results of the Coloured Samples

K.1. Results of the analysis of four samples of deliberately coloured glass which had been removed from earlier consideration. They consisted of two natron and two plant ash glasses. Colouration is by lead and copper for the natron glasses and only copper in the plant ash glasses. The low MgO and high CaO of the plant ash glass suggest an Eastern Mediterranean ash type.

Major and minor oxides in wt %

Sample		Colour	Colourant	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	MnO	TiO_2	Fe_2O_3	PbO	CuO
JER 5124 09	natron	blue	Pb, Cu	19.26	0.45	2.82	64.62	0.09	1.26	0.37	2.20	0.03	0.24	1.10	2.48	4.31
RAM 3592 02	natron	greenish	Pb	14.84	0.58	2.52	65.67	0.08	0.99	0.39	9.61	0.07	0.26	0.90	3.90	0.01
TIB 5583 10	plant ash	partly opaque/ dull turquoise	Cu	13.66	3.12	0.90	66.02	0.26	0.79	2.07	9.34	0.08	0.07	0.39	0.68	1.87
AY 2989 16	plant ash	dark blue	Cu	11.91	2.53	1.83	66.11	0.38	0.80	2.25	8.17	1.00	0.09	0.56	0.30	3.56

Trace oxides in ppm

Li_2O	B_2O_3	V_2O_5	Cr_2O_3	CoO	NiO	ZnO	GaO	As_2O_3	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_3	MoO	Ag	Cd	In	SnO_2	Sb_2O_3	Cs_2O	BaO
3.0	201	30.2	45.8	10.3	58.5	3491	4.2	129	5.6	166	7.3	158	3.5	0.1	60.7	0.1	8.7	2897	221.3	bdl	175
8.5	247	35.7	38.0	8.7	8.2	46	3.9	13	5.6	239	8.5	239	4.3	0.3	1.3	0.1	1.3	422	57.4	0.06	185
13.7	309	18.8	17.8	7.2	39.2	1002	1.9	104	10.9	579	4.7	55	1.6	1.0	12.0	0.1	15.4	5013	33.9	0.17	95
bdl	274	23.1	n/a	10.5	39.4	1191	3.1	186	13.5	594	7.9	55	2.1	2.7	22.5	0.1	6.8	2170	59.9	0.04	294

La_2O_3	CeO_2	PrO_2	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	HfO_2	Ta_2O_3	WO	Au	Bi	ThO_2	UO_2
7.3	14.4	1.74	7.19	1.46	0.38	1.30	0.21	1.14	0.24	0.67	0.10	0.79	0.11	3.28	0.19	0.66	1.13	8.30	1.32	1.15
8.4	16.3	1.92	7.69	1.55	0.38	1.36	0.21	1.26	0.26	0.73	0.12	0.80	0.12	4.75	0.21	0.10	bdl	3.29	1.65	1.07
6.1	11.3	1.31	5.02	1.00	0.22	0.85	0.13	0.69	0.13	0.35	0.05	0.38	0.05	1.24	0.08	0.06	0.10	2.39	1.00	0.53
7.4	13.6	1.68	6.72	1.39	0.32	1.14	0.20	1.10	0.23	0.60	0.09	0.57	0.09	1.23	0.11	2.52	0.48	6.10	1.00	0.51

Appendix L: Trona Content of Glass and Cost Calculation

This section calculates the amount of trona that is required for 150g of glass with a soda content of 15%, which is similar to the soda content within Apollonia glass.

Soda (Na_2O) has a molecular mass of 62. Trona ($Na_2CO_3.NaHCO_3.2H_2O$) has a molecular mass of 225.

150/62 = 2.42 Moles of soda in 150g of glass

Trona contains 1.5 soda molecules so less trona is required to produce the same amount of soda.

The amount of trona required to make 150g of glass is:

225/1.5 = 150.

2.42 x 150 = 360g of trona.

Therefore, 360g of trona is required for 150g of soda in 1000g of glass.

From this, a cost of natron for an amount of glass can be calculated.

At the extraction cost (see Chapter 9) of 2 dinars per qintar of natron, the natron in glass would cost 0.36 x 2 = 0.72 dinars

At the 12th century market cost of 70 dinars per qintar of natron, the natron glass would cost 0.36 x 70 = 25.2 dinars.

At the 13th century market cost of 300 dinars per qintar of natron, the natron glass would cost 0.36 x 300 = 108 dinars.